Bulletin
of
The Geological Society of America

VOLUME 54 AUGUST 1, 1943 NUMBER 8

CONTENTS

PAGES

Spectrographic analysis of New England granites and pegmatites. By John A. Shimer 1049–1066

Ordovician clastic sedimentary rocks in Pennsylvania. By Bradford Willard 1067–1122

Structure of central part of Sawtooth Range, Montana. By Charles Deiss 1123–1168

Application of geology to the principles of war. By Charles E. Erdmann 1169–1194

Bibliography on the interpretation of aerial photographs and recent bibliographies on aerial photography and related subjects. By Genevieve C. Cobb 1195–1210

Metamorphism of extrusives by basic intrusives in the Keweenawan of Minnesota. By George M. Schwartz 1211–1226

Subscription, $10 per year.

Publication Office: Florida Avenue and Eckington Place, Washington, D. C.

Communications for publication should be addressed to The Geological Society of America, Dr. H. R. Aldrich, Secretary, 419 West 117th Street, New York, N. Y.

NOTICE.—In accordance with the rules established by the Council, claims for non-receipt of the preceding number of the Bulletin must be sent to the Secretary of the Society within three months of the date of the receipt of this number in order to be filled gratis.

Entered as second-class matter in the Post-Office at Washington, D. C., under the Act of Congress of July 16, 1894.

Accepted for mailing at special rate of postage provided for in Section 1103, Act of October 3, 1917, authorized on July 8, 1918.

PRESS OF JUDD & DETWEILER, INC., WASHINGTON, D. C.

PAPERS IN PRESS FOR FORTHCOMING ISSUES

Geology of the Santiago Peak Quadrangle, Texas. By G. K. Eifler, Jr.

Packing in Ionic Minerals. By H. W. Fairbairn

History of the Development of Geologic Maps. By H. Andrew Ireland

Perennially Frozen Ground in Alaska: Its Origin and History. By Stephen Taber

Reverse Faulting North of Harrisburg, Pennsylvania. By Ernst Cloos and Carl H. Broedel

Late Pleistocene Coast Range Orogenesis in Southern California. By Thomas L. Bailey

Fossiliferous Tills and Intertill Beds of Cape Cod, Massachusetts. By Robert W. Sayles and Arthur S. Knox

Recrystallization and Flowage in Appalachian Quartzite. By Robert E. Fellows

Pre-Cretaceous of Colombia. By D. Trumpy

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 54, PP. 1049-1066, 4 FIGS. AUGUST 1, 1943

SPECTROGRAPHIC ANALYSIS OF NEW ENGLAND GRANITES AND PEGMATITES

BY JOHN ASA SHIMER

CONTENTS

	Page
Abstract	1049
Introduction and acknowledgments	1050
Method of analysis	1051
Qualitative results	1053
General statement	1053
Areal relationships	1054
Granites	1054
Granite micas	1056
Pegmatite micas	1056
Granite and pegmatite relationships	1059
Granites compared with pegmatites	1059
Granite feldspars compared with pegmatite feldspars	1059
Granite micas compared with pegmatite micas	1059
Miscellaneous relationships	1059
Comparison of minor element content of gneissic and massive granites	1059
Grain size and minor element content of granites	1059
Correlation between amount of biotite and minor element content of granites	1059
Quantitative results	1061
Descriptions of specimens	1061
References cited	1065

ILLUSTRATIONS

Figure	Page
1. Qualitative granite analyses	1054
2. Map of qualitative spectrographic analyses of granites	1055
3. Map of qualitative spectrographic analyses of granite micas	1057
4. Map of qualitative spectrographic analyses of pegmatite micas	1058

ABSTRACT

A number of New England "granites" and their associated pegmatites were analyzed spectrographically for their minor element content. The analyses were made of the rocks as a whole and of the rock-forming minerals separately.

(1) Each granite had well-marked minor element characteristics whereby it could be distinguished from the others.

(2) Almost invariably the granites and the granite minerals had a greater variety of minor elements than the adjacent pegmatites and pegmatite minerals; when the same element was found in both environments it was more abundant in the granites.

(3) The following pairs of elements varied together: barium and strontium, and

vanadium and chromium. The barium-strontium relationship was true in all mineral and rock samples; that of vanadium-chromium was marked only in the granites.

(4) Biotite, where present in a granite, contained the bulk of the minor elements of the rock.

(5) A genetic as well as an areal kinship between many of the granites and pegmatites was suggested.

(6) Most elements were preferentially concentrated in the biotites of a two-mica granite, only barium, scandium, sodium, and strontium being concentrated in the muscovites.

INTRODUCTION AND ACKNOWLEDGMENTS

The rocks studied were chiefly granites but included some quartz monzonites. The term minor element is here applied to an element present in an amount of less than 1 per cent. Analyses and comparisons were made on both the rock as a whole and the major constituent minerals separately. The minerals separated were quartz, feldspar, muscovite, and biotite. All white micas were included under muscovite, and black micas under biotite. No attempt was made to separate the various types of feldspars. The modal analyses give the percentage of the different types of feldspars in each granite.

Most of the granites were rather fine-grained, and some of the mineral samples could not be freed from inclusions or adhering particles of other minerals. All the mineral samples from the pegmatites were free from inclusions.

The quartz contained fewer minor elements than the feldspars and micas; so, if, as is usual, small particles of feldspar or mica should adhere to a number of quartz grains, an analysis of such quartz grains would not give a true analysis of the quartz as such. Thus, quartz analyses are not included.

The graphic plots of analyses for "white mica" and "black mica" are characteristic for each of these minerals. For example, zirconium may be present in biotite as small zircon crystal inclusions, and other minor elements may be present in inclusions or in solid solution, but the kind and proportions of minor elements in the biotite are characteristic for that mineral.

To obtain a close areal relation between the granite and pegmatite samples only those pegmatites actually within a granite mass or within a few feet of its border were chosen. For this reason, and because of the desired freshness of the rock, most of the specimens were taken from granite quarries. All specimens came from the New England Province, including Maine, New Hampshire, Vermont, Massachusetts, and Connecticut. For a discussion of current theories on the origin and classification of pegmatites, *see* Hess (1925), Landes (1933), Schaller (1933), and Fersmann (1931). Kemp (1924) gives a good review of the ideas on pegmatites up to that time.

The following data are included: (1) graphic plots of the qualitative analyses of the granites, granite micas, and pegmatite micas; (2) five sets of graphic plots of analyses of two or more granite specimens from the same quarry (indicating the reproducibility of analyses of different specimens from the same quarry); (3) quantitative analyses of both granite and pegmatite feldspars.

Much work has been done in the last 20 years on the spectrographic analyses of minerals and rocks, especially abroad. A detailed bibliography is not included, but the following articles are of interest in connection with the present study. Goldschmidt (1933) discusses the distribution of minor elements in pegmatites between geologic provinces and (1937) the principles of distribution of chemical elements in minerals and rocks from the crystal chemistry standpoint.

Van Aubel (1935) found that the distribution of minor accessory elements in some Belgian Congo fragments of tantalo-columbite, samarskite, and euxenite varied according to the stream from which the specimen came.

The work was undertaken after consultation with Professor W. H. Newhouse, of the Department of Geology at the Massachusetts Institute of Technology, who helped in all phases of the work. Mr. Richard Jarrell, of the Cabot Spectrographic Laboratory of the Geology Department of the Massachusetts Institute of Technology, assisted in the laboratory technique.

METHOD OF ANALYSIS

The present problem is peculiarly adapted to the spectrograph, which offers the quickest, cheapest, and, for percentages of less than 1 per cent, generally the most accurate method of analysis for most of the elements in mineral and rock samples.

Qualitative analyses were made of most of the mineral and rock samples, and quantitative analyses of the granite and pegmatite feldspars.

The instrument used is in the Cabot Spectrographic Laboratory of the Department of Geology at the Massachusetts Institute of Technology. It is a Wadsworth mounted 21-foot concave grating instrument with 30,000 lines to the inch and 6 inches of ruling. The dispersion is about 2.5 Ångstroms per millimeter.

The spectra were taken on 4- by 29½-inch Eastman antihalation safety process film.

Both the cathode-layer and the positive-column methods were tried on a series of mineral and rock samples, and the former proved the better

because there was less background, the element lines were stronger for the same amount of sample, and smaller samples were needed.

The fundamental difference between the two methods is that in the cathode-layer method the lower electrode, which contains the sample,

TABLE 1.—*Element lines used for qualitative and quantitative work*

Element	Symbol	Wave length in A. U.
Aluminum	Al	3961.5
Barium	Ba	4554.0
Calcium	Ca	4226.8
Cobalt	Co	3453.5
Chromium	Cr	4254.3
Copper	Cu	3247.6 and 3274.0
Iron	Fe	4404.8
Gallium	Ga	4172.0
Potassium	K	4044.2
Lanthanum	La	4333.8
Magnesium	Mg	2852.1
Manganese	Mn	4034.5
Sodium	Na	3302.9 and 3302.3
Nickel	Ni	3414.8
Scandium	Sc	4246.8
Silicon	Si	2987.6 (internal standard)
Strontium	Sr	4607.3
Titanium	Ti	3361.2
Vanadium	V	4379.2
Yttrium	Y	4102.4
Zinc	Zn	3345.5
Zirconium	Zr	3392.0

is the cathode, and only the light near the cathode passes into the spectrograph. In the positive-column method the bottom electrode is the anode, and light from the central part of the arc passes into the spectrograph.

The qualitative analyses were made from a partly quantitative basis as follows. Instead of merely noting the presence or absence of an element, an estimate was made of the relative density of the element line when compared with the same line in other spectra on the same plate. Since density measures amount, sample 1, for example, has more of an element than sample 2 and less than sample 3. This, however, gives no indication of absolute quantities. Repeated runs of the same sample checked very well when run on the same plate.

The quantitative analyses were made by the internal-standard method. Silicon, present in all samples, proved to be satisfactory for the internal standard. Table 1 gives the wave lengths of the element lines used.

For a discussion of quantitative spectrographic technique, *see* Brode (1939) and Strock (1936) (cathode-layer method). Bray (1942) also outlines the same general procedure used in the present work. Meggers, Kiess, and Stimson (1922-1923) give a good background for a study of quantitative spectrographic methods. Fitch (1930) and Van Tongeren (1938) give methods for spectrographic analysis of minerals and also many analyses.

QUALITATIVE RESULTS

GENERAL STATEMENT

All qualitative results are partly quantitative, since relative amounts of a given element are compared in different samples. Since comparisons between samples can be made only on the same plate, different combinations of groups of samples were run on different plates in order to bring out a variety of relationships.

Two major relationships were obtained: (1) The same types of samples from different localities were run on the same plate so as to compare the locality variations; and (2) the same minerals from granite and pegmatite from the same locality were run on the same plate to determine the relative amounts of minor elements in the two different environments.

Three sets of data were obtained to illustrate the first relationship. Analyses were made of (1) granites from all the localities; (2) granite micas from all the localities; and (3) pegmatite micas from all the localities. Two sets of data were obtained to illustrate the second relationship: (1) The granite feldspars were compared with the pegmatite feldspars; and (2) the granite micas were compared with the pegmatite micas.

As stated, an attempt was made to compare quartz from the granites with quartz from the pegmatites, but the former were "salted" to such an extent by adhering foreign matter that the results had little meaning.

Significant conclusions are outlined in the following section. Some of the data concerning locality variations of the same mineral or rock are presented in the form of maps (Figs. 1-4). No data concerning variations of minor elements between granites and pegmatites are included.

Some results are obviously well known but are included for completeness and as further substantiation of their validity.

In forming the maps, 12 elements were chosen which were nearly always present in the samples and which showed the most variations. For consistency the same elements were chosen for each mineral and rock whether they were minor elements or essential. Twelve spoked wheels were plotted on the maps, each spoke representing a given element, and the length of the spoke the relative amount of that element compared to the same element at the other localities.

Comparisons of relative amounts between quarries can be made when only one element is considered; the ratio of the lengths of spokes when two elements are considered has no meaning, whether on the same or on two different wheels.

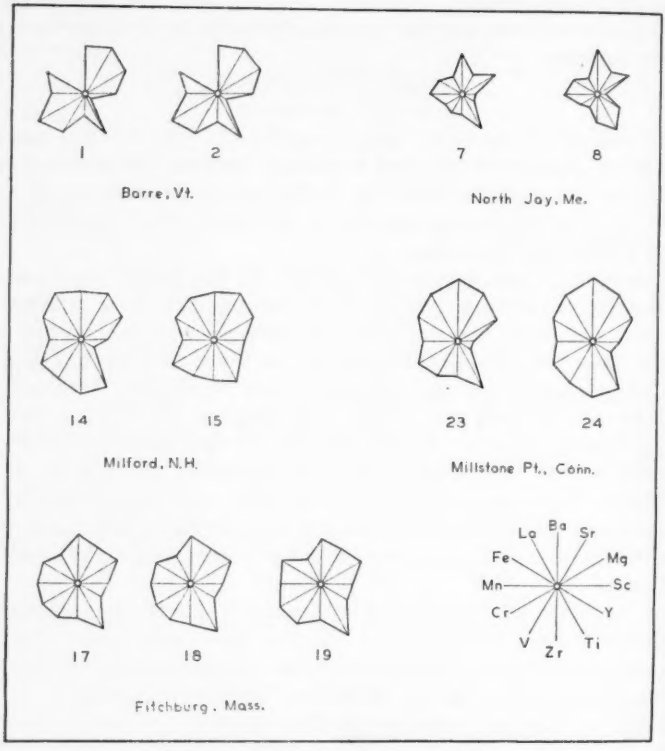


FIGURE 1.—*Qualitative granite analyses*

These show similarity of analysis diagrams of different specimens from same quarry.

AREAL RELATIONSHIPS

Granites.—The following elements, both minor and essential, were noted in one or more of the granite specimens: Al, Ba, Ca, Cr, Cu, Fe, Ga, K, La, Mg, Mn, Na, Sc, Si, Sr, Ti, V, Y, and Zr.

The following specimens, arranged in groups, came from the same quarries: 1 and 2, 7 and 8, 14 and 15, 17, 18, and 19, 23 and 24.

Figure 1 represents graphically the analyses of these granites. The specimens from the same quarries were generally 100 to 200 feet apart,

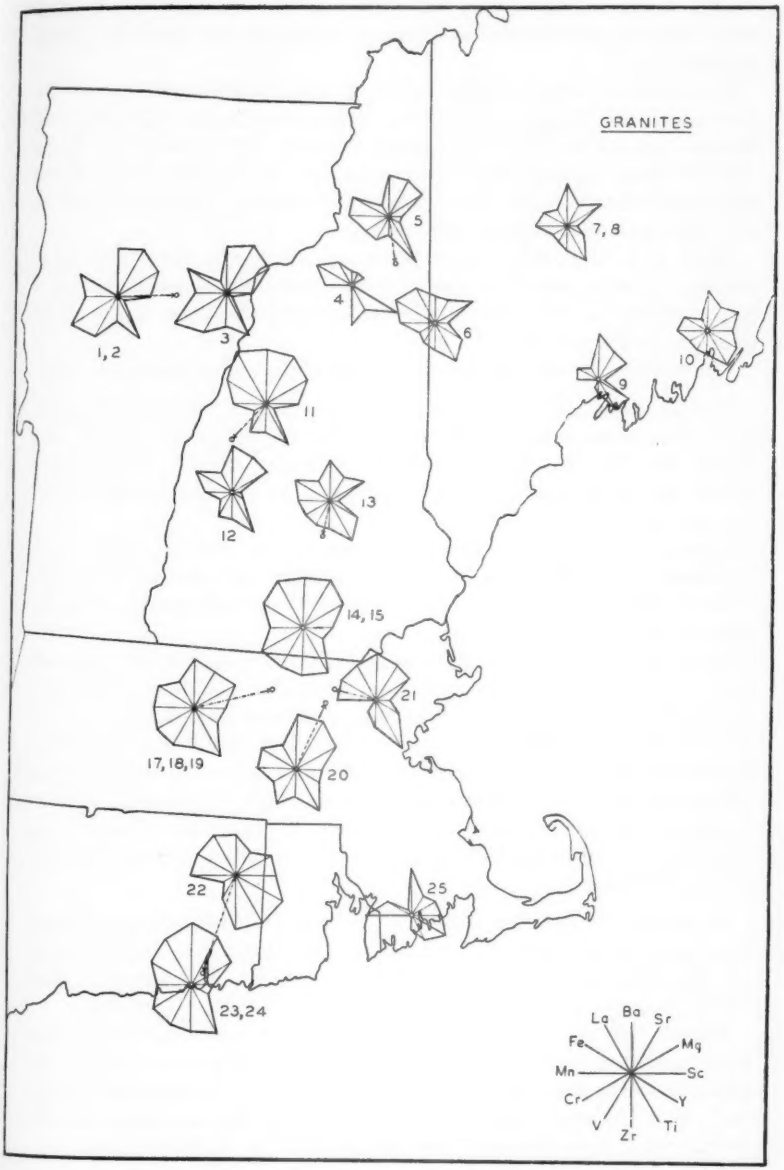


FIGURE 2.—*Map of qualitative spectrographic analyses of granites*
Lengths of radii of diagrams give relative amounts of a given element in different localities.

and the results indicate clearly that a given granite has definite individual minor element characteristics, certainly as regards the area of a large quarry.

The results of Bray's (1942) spectrographic analyses of some of the Colorado Front Range igneous rocks demonstrate further the ability of the spectrograph to differentiate among granites. By means of the minor elements Bray distinguished between any of the igneous rocks of the Jamestown district of the Front Range of Colorado. Each rock had its own suite and abundance of minor elements.

There is a rough relationship between barium, strontium, and magnesium. A large amount of one of these elements is accompanied by a large amount of the others. The relationship between barium and strontium is the closest.

Correlation between the amounts of vanadium and chromium is close.

Granite micas.—The following elements, both minor and essential, were noted in one or more of the biotites: Al, Ba, Ca, Co, Cr, Cu, Fe, Ga, K, La, Mg, Mn, Na, Ni, Sc, Si, Sr, Ti, V, Y, Zn, and Zr. One or more of the muscovites had all the elements found in the biotites except Co, Ni, and Zn.

Analyses of specimens from the same quarry checked fairly well, especially when differences between one quarry and another were considered. The reproducibility was not, however, so well marked as in the granites from the same quarry.

Figure 3 shows that: (1) Biotites generally have more minor elements than do muscovites; (2) in the two-mica granites all elements are more abundant in the biotites, except barium, scandium, and strontium, which are always more abundant in the muscovites, and vanadium which occurs in about equal amounts in the biotites and muscovites; (3) in general, an abundance of minor elements in a granite mica corresponds with an abundance in the granite as a whole, and a pegmatite mica with an abundance of minor elements in general cuts a granite whose mica also has an abundance.

Pegmatite micas.—The following elements, both minor and essential, were noted in one or more of the biotites: Al, Ba, Ca, Cr, Cu, Fe, Ga, K, La, Mg, Mn, Na, Ni, Sc, Si, Sr, Ti, V, Y, and Zr. The muscovites had all the elements found in the biotites except Cr, La, Ni, Y, and Zr.

Figure 4 shows that: (1) pegmatite biotites have invariably more minor elements than the muscovites; (2) pegmatite micas have fewer minor elements than the corresponding micas from the adjacent granite, and, when the same element is present in both the pegmatite and the granite mica, it is invariably less abundant in the pegmatite mica.

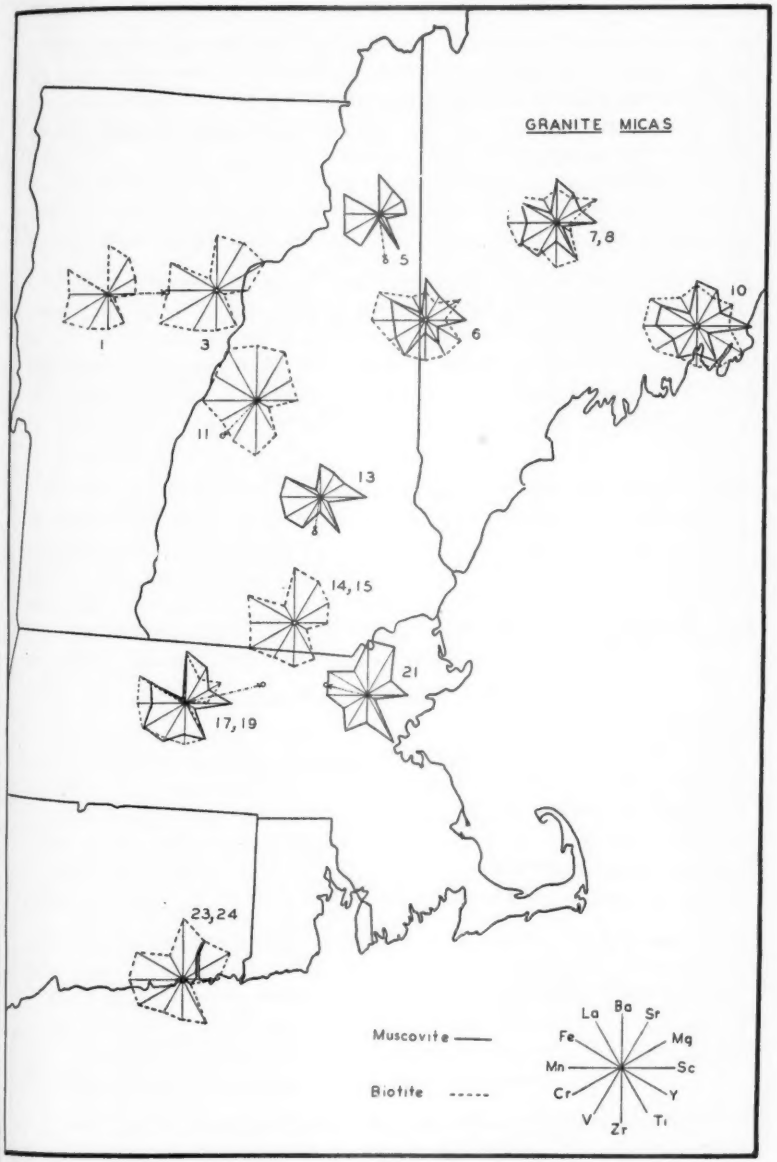


FIGURE 3.—*Map of qualitative spectrographic analyses of granite micas*
Lengths of radii of wheel diagrams give relative amounts of a given element in different samples.

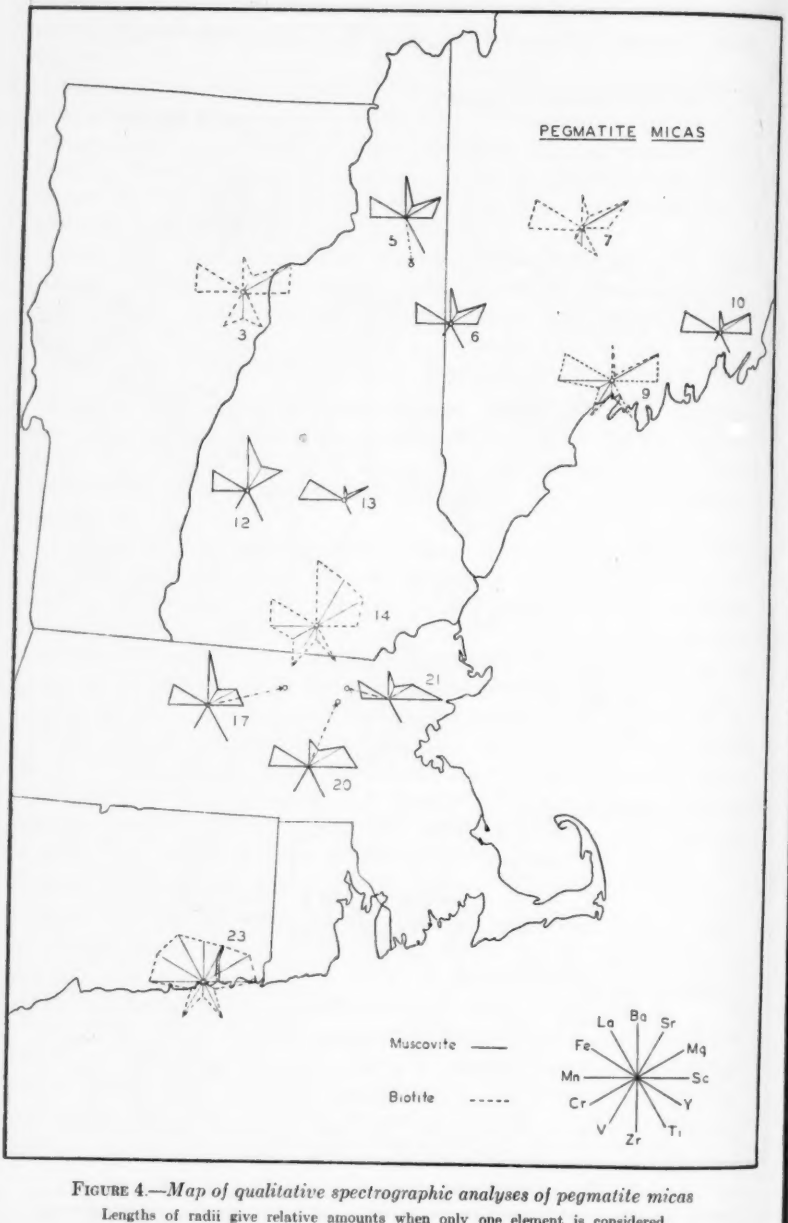


FIGURE 4.—*Map of qualitative spectrographic analyses of pegmatite micas*
Lengths of radii give relative amounts when only one element is considered.

GRANITE AND PEGMATITE RELATIONSHIPS

Granites compared with pegmatites.—The minor element content of 24 pegmatites was compared with that of the respective granites cut by the pegmatites. The results showed conclusively a marked concentration in the granites when compared with the pegmatites. The one element showing a marked increase in the pegmatites was potassium. This, of course, is not a minor element. The sampling of an individual pegmatite would be open to some doubt. However, when 24 granite-pegmatite pairs showed the relations stated above, the results had a definite meaning.

Granite feldspars compared with pegmatite feldspars.—A number of granite feldspars were compared with the corresponding pegmatite feldspars. The results showed an increase of potassium (not a minor element) in the pegmatite feldspars and, in general, a decrease in all minor elements. These results check the quantitative results obtained on the feldspars as well as the data obtained from comparing the granites with the pegmatites.

Granite micas compared with pegmatite micas.—On the whole, minor elements were more abundant in the granite micas than in the corresponding pegmatite micas, and the biotites had more than the muscovites. When both types of mica occurred in either a granite or a pegmatite, scandium and sodium were definitely concentrated in the muscovites. Ca, La, Mn, Ti, and Zr were definitely concentrated in the biotites, and the other elements gave inconclusive results.

MISCELLANEOUS RELATIONSHIPS

Comparison of minor element content of gneissic and massive granites.—The following granite specimens are gneissic: 5, 17, 18, 19, 20, 21, 22, and 25. The major difference between these and the massive granites is in the barium-strontium ratios of the quantitatively analysed feldspars. (*See* Table 2.) The barium:strontium ratio of the feldspar from a massive granite is in general much closer to that of the feldspar from the adjacent pegmatite than is that of the feldspar from a gneissic granite.

Grain size and minor element content of granites.—The granites varied very little in grain size; nine-tenths were fine-grained. However, an attempt was made to arrange them visually according to grain size, and a tentative very rough correlation was found between the grain size of the granites and the abundance of minor elements—the finer-grained the granite, the more abundant the minor elements.

Correlation between amount of biotite and minor element content of granites.—A very good correlation existed between the biotite content

TABLE 2.—*Quantitative analyses of granite and pegmatite feldspars*

Figures give weight percentage.

No.	Granite or Pegmatite	Ba	Ga	Fe	La	Mn	Sr	Ti	V	Y	Zr	Ba/Sr
1	G	.21	.003	.13	.....	.009	.12	.026	.....	.....	.....	1.7
	P	.03	.004	.15	.....	.003	.03	.025	.....	.....	.....	1.0
3	G	.11	.006	.12	.....	.002	.082	.029	.....	.....	.021	1.3
	P	.02	.005	.07	.....	.....	.012	.....	.....	.....	.....	1.7
5	G	.06	.002	.19	.....	.006	.011	.032	.....	.....	.....	5.5
	P	.06	.002	.....	.....	.....	.005	.....	.....	.....	.....	12.0
6	G	.05	.004	.06	.....	.004	.005	.....	.....	.....	.....	10.0
	P	.04	.004	.03	.....	.003	.005	.....	.....	.....	.....	8.0
7	G	.03	.003	.08	.02	.002	.006	.011	.....	.01	.02	5.0
	P	.02	.003	.03	.....	.001	.009	.....	.....	.....	.....	2.2
8	G	.04	.004	.08	.....	.003	.008	.002	.....	.....	.....	5.0
	P	.01	.003	.05	.....	.003	.004	.....	.....	.....	.....	2.5
9	G	.01	.003	.24	.....	.002	.004	.006	.....	.....	.....	2.5
	P	.10	.004	.06	.....	.002	.015	.....	.....	.....	.....	6.7
10	G	.01	.002	.10	.....	.004	.003	.....	.....	.01	.....	3.3
	P	.001	.008	.07	.....	.027	.0004	.....	.....	.....	.....	2.5
	P	.001	.006	.19	.....	.020	.0003	.....	.....	.....	.....	3.3
11	G	.30	.004	.11	.....	.004	.072	.004	.....	.....	.....	4.2
12	G	.06	.004	.18	.....	.005	.026	.033	.....	.....	.....	2.3
	P	.10	.004	.....	.....	.004	.035	.....	.....	.....	.....	2.9
13	G	.05	.005	.21	.....	.020	.026	.037	.....	.....	.....	1.9
	P	.001	.005	.....	.....	.....	.001	.....	.....	.....	.....	1.0
14	G	.22	.004	.19	.....	.005	.100	.092	.001	.....	.....	2.2
	P	.15	.005	.13	.....	.004	.058	.....	.....	.01	.....	2.6
15	G	.17	.006	.14	.05	.005	.053	.017	.....	.....	.04	3.2
	P	.25	.007	.16	.....	.011	.098	.....	.....	.04	.....	2.6
16	G	.28	.005	.10	.....	.....	.12	.....	.....	.....	.....	2.3
17	G	.23	.005	.22	.....	.....	.057	.074	.....	.....	.....	4.0
	P	.04	.004	.04	.....	.003	.005	.005	.....	.....	.....	8.0
19	G	.20	.005	.06	.01	.002	.028	.023	.....	.....	.....	7.1
	P	.04	.003	.04	.....	.001	.026	.003	.....	.....	.....	1.5
20	G	.15	.001	.20	.....	.002	.047	.....	.....	.....	.....	3.2
	P	.003	.002	.05	.....	.003	.005	.....	.....	.....	.....	0.6
21	G	.0001	.005	.12	.....	.004	.001	.008	.....	.....	.....	0.1
	P	.04	.003	.07	.....	.....	.007	.....	.....	.....	.....	5.7
22	G	.02	.006	.88	.....	.....	.001	.016	.....	.....	.05	20.0
	P	.05	.005	.29	.....	.....	.004	.....	.....	.....	.....	12.5
23	G	.30	.004	.64	.05	.010	.086	.076	.....	.....	.02	3.5
	P	.05	.011	.11	.02	.003	.023	.012	.....	.....	.....	2.2
24	G	.28	.002	.19	.04	.004	.072	.014	.....	.....	.04	3.9
	P	.002	.009	.19	.....	.003	.058	.010	.....	.....	.....	0.4
25	G	.04	.004	.14	.....	.020	.001+	.008	.....	.....	.....	40.0
	P	.01	.007	.07	.....	.002	.001−	.....	.....	.....	.....	10.0

of the granites (obtained from the modal analyses) and the amount of minor elements in the rock. The higher the biotite content the more abundant the minor elements. This was true except in granite specimen number 22 (aegerite granite), which had very little biotite but abundant minor elements. In this case the aegerine itself is probably the host for the minor elements.

QUANTITATIVE RESULTS

Table 2 gives the data on the pegmatite and granite feldspars. Quantitative analyses of only the minor elements were made.

As in all the other analyses, the minor elements were more abundant in the granite mineral than in the corresponding pegmatite mineral.

In almost all cases there was more barium than strontium in a sample. Also, in general, where the barium-strontium ratio was large in a granite feldspar it was large in the corresponding pegmatite feldspar. Such a relationship, where present, suggests a common source for the granite and the pegmatite.

Other data which substantiate the common origin are: (1) The same kind of mica usually occurs in both a granite and the cutting pegmatite; and (2) Abundant minor elements in a granite mineral correspond roughly with an abundance in a pegmatite mineral. At places this threefold indication of common origin is better than at others.

Bray (1942) found that rather generally in the Front Range granite of the Jamestown district of Colorado the barium-strontium ratio, $\frac{Ba}{Sr}$, was smaller in the pegmatites than in the granites. He attributed this to the fact that the strontium atom is smaller than the barium atom and, at low temperatures, at which pegmatites are formed, is given preference as being able to fit into the more well-ordered, low-temperature feldspar structure. The present data substantiate this in 14 out of 20 pairs.

DESCRIPTIONS OF SPECIMENS

Except when otherwise noted, the granites are rather fine-grained. The pegmatites rarely have crystals in excess of 1-1½ inches.

All specimen numbers, unless otherwise noted, refer to a granite-pegmatite pair, the granite in all cases from within 2 to 3 feet of the pegmatite.

The modal analyses were made by the author. *See* Dale (1911; 1923) for further descriptions of most of the quarries.

(1) Pirie quarry, southern part of Barre district, Vermont. Not many pegmatites in this district; Pirie quarry has most. Biotite granite. Pegmatite 3-foot, branching.
(2) Same quarry as No. 1. Granite specimen from the dump.

Modal Analysis of Granite

Quartz	14.1
Orthoclase	23.2
Plagioclase (Oligoclase)	50.5
Muscovite	2.9
Biotite	8.9
Apatite	tr
Opaque minerals	tr

Plagioclase largely sericitized.

(3) Benzie quarry, Groton, Vermont about 1¼ miles south of the town. Very few pegmatites. Biotite granite. Pegmatite 6 inches wide and rather sharp-walled.

Modal Analysis of Granite

Quartz	54.5
Orthoclase	13.8
Plagioclase (Andesine)	19.4
Muscovite	1.6
Biotite	10.6
Apatite	tr
Sphene	tr

(4) Fabyan House, New Hampshire. No pegmatites. Granite from bed of Ammonoosuc River. Sheets averaging 2 feet thick. Conspicuous. Granite medium- to coarse-grained.

Modal Analysis of Granite

Quartz	41.5
Orthoclase	31.6
Plagioclase (Andesine–Oligoclase)	24.5
Muscovite	2.2
Biotite	tr
Apatite	tr

Orthoclase somewhat kaolinized.

(5) Randolph, New Hampshire, high point on Dolly Copp Road. Specimens from within granite mass but within about 100 feet of granite-schist contact. Binary gneissic granite. Pegmatite, flat-dipping, of variable thickness.

Modal Analysis of Granite

Quartz	26.5
Orthoclase	30.7
Plagioclase (Oligoclase)	32.5
Muscovite	8.4
Biotite	1.8
Apatite	tr

(6) Eagle Gray quarry, Fryeburg, Maine. At northeast foot of Stark's Hill, about 1¼ miles south of Fryeburg village. Muscovite-biotite granite. One-foot pegmatite with fairly sharp walls.

Modal Analysis of Granite

Quartz	27.5
Orthoclase	28.1
Plagioclase (Oligoclase)	36.4
Muscovite	3.6
Biotite	4.0
Apatite	tr
Opaque mineral	tr

(7) Maine and New Hampshire Granite Corporation quarry, North Jay, Maine. Granite in places gneissic. Biotite-muscovite granite (massive). Pegmatite 2 feet thick with fairly sharp walls and steep dip.

MODAL ANALYSIS OF GRANITE

Quartz	42.1
Orthoclase	18.8
Plagioclase (Oligoclase)	31.2
Muscovite	4.0
Biotite	4.0
Apatite	tr

(8) Same quarry as No. 7. Pegmatite from a gneissic streak which runs through massive granite. Streak is about 30 feet wide, with a steep dip, and is made up of gneissic granite and pegmatite stringers oriented with streak as a whole. Granite specimen is from massive phase just outside streak.

(9) Brunswick, Maine. Quarry about 3 miles west of center of town on secondary road which parallels U. S. route 1 about ¼ mile to the south. Schist outcrops within ¼ mile of quarry. Biotite granite, coarse-grained. Pegmatite flat-lying with fairly sharp contacts.

MODAL ANALYSIS OF GRANITE

Quartz	41.8
Orthoclase	14.4
Plagioclase (Oligoclase)	41.9
Muscovite	0.4
Biotite	1.3

Plagioclase largely sericitized.

(10) Waldeboro quarry, Waldeboro, Maine. On U. S. route 1 about 1¼ miles north of the town. Muscovite-biotite granite. Pegmatite 4 inches thick, with sharp contacts and steep dip.

MODAL ANALYSIS OF GRANITE

Quartz	35.4
Orthoclase	28.2
Plagioclase (Oligoclase-Andesine)	30.7
Muscovite	3.3
Biotite	2.3
Apatite	tr
Sphene	tr

(11) Enfield, New Hampshire, 3½ miles north of town and ⅛ mile east of the road. No pegmatites, granite crisscrossed with aplite dikes. Biotite granite.

MODAL ANALYSIS OF GRANITE

Quartz	31.3
Orthoclase	40.3
Plagioclase (Oligoclase)	26.4
Biotite	1.8
Apatite	tr
Opaque minerals	tr

(12) Perry-Sunapee quarry, Sunapee, New Hampshire. Many pegmatites up to 1 foot thick, contacts sharp, thickness uniform. Muscovite-biotite granite. Pegmatite 4 inches thick.

MODAL ANALYSIS OF GRANITE

Quartz	42.1
Orthoclase	15.2
Plagioclase (Oligoclase)	31.6
Muscovite	7.2
Biotite	3.4
Apatite	tr

(13) Swenson quarry, Concord, New Hampshire. Muscovite-biotite granite. One 3-inch pegmatite, with sharp contacts, very straight and uniform as far as exposed (about 200 feet).

Modal Analysis of Granite

Quartz	39.7
Orthoclase	23.6
Plagioclase (Oligoclase-Andesine)	28.6
Muscovite	4.8
Biotite	3.1
Apatite	tr
Opaque minerals	tr

(14) Young's quarry, Milford, New Hampshire, on route 101A 1.7 miles southeast of the town and 0.1 mile southeast of the road. Dark granite. A massive phase overlain by granite-gneiss, which has many pegmatitic streaks and which apparently join those in the massive granite. Specimen about 50 feet from gneiss-granite contact. Two-inch branching pegmatite, cutting massive granite.

Modal Analysis of Granite

Quartz	37.1
Orthoclase	29.6
Plagioclase (Oligoclase)	24.1
Muscovite	0.6
Biotite	8.3
Apatite	tr
Opaque minerals	tr

(15) Same quarry as No. 14. Granite is massive type, and a horizontal pegmatite separates it from overlying gneiss. Pyrite is local, especially in pegmatite.

(16) Same quarry as No. 14. No granite specimen. Pegmatite from the gneiss, about 5 feet from contact with massive granite.

(17) McCauliff quarry, Fitchburg, Massachusetts, on west side of Rollstone Hill. Especially rich in pegmatites and noted for those bearing tourmaline. Muscovite-biotite granite-gneiss. Pegmatite has a variable width, 1-2 feet, with relatively sharp contacts, carries tourmaline in places, and is bordered by a muscovite-rich band. (*See* Hitchen (1935) for a discussion of the Fitchburg Pegmatites.)

(18) Same quarry as No. 17. Granite specimen from within 200 feet of No. 17.

Modal Analysis of Granite

Quartz	30.8
Orthoclase	33.5
Plagioclase (Oligoclase)	27.4
Muscovite	3.3
Biotite	4.8
Apatite	tr
Opaque minerals	tr

(19) Same quarry as No. 17. Two-inch pegmatite which has mica flakes oriented with grain of enclosing granite as well as a number of schist inclusions in granite.

(20) Harris quarry. About ½ mile north of North Acton station, Massachusetts. Very few pegmatites. Biotite-muscovite granite gneiss. One-foot pegmatite with sharp walls.

Modal Analysis of Granite

Quartz	26.1
Orthoclase	12.0
Plagioclase (Oligoclase)	53.3
Muscovite	3.1
Biotite	4.8
Apatite	tr
Opaque minerals	tr

(21) H. N. Fletcher quarry, south side of Snake Meadow Hill, Westford, Massachusetts. Many small dikes of fine-grained granite, aplite and pegmatite. Muscovite-biotite granite gneiss. A 2-inch pegmatite with sharp contacts. Quartz not prominent.

MODAL ANALYSIS OF GRANITE

Quartz	36.9
Orthoclase	33.1
Plagioclase (Oligoclase-Andesine)	21.0
Muscovite	6.6
Biotite	1.5
Garnet	tr
Opaque minerals	tr

Plagioclase largely sericitized.

(22) Scott quarry, Quaker Hill Village, Connecticut, 3 miles north of New London. Abandoned, on main road just south of village and appears as a road cut. Aegerite granite gneiss. Pegmatite, small, with relatively sharp contacts.

MODAL ANALYSIS OF GRANITE

Quartz	47.6
Orthoclase	32.2
Plagioclase (Andesine)	16.7
Aegerine	2.5
Apatite	tr
Opaque minerals	tr

(23) Millstone quarries, Millstone Point, Connecticut. Specimens from a few tens of feet of border of granite mass. Granite is overlain by a gneiss, remnants of which are in granite. Biotite granite. A 3-inch pegmatite with very sharp walls, which runs straight for about 200 feet (only part exposed).

(24) Same quarry as No. 23, and from within 5 feet. Granite the same. Pegmatite, in striking distinction to that in pair No. 23, grades into granite and occurs in patches with prominent thinning and thickening.

MODAL ANALYSIS OF GRANITE

Quartz	21.2
Orthoclase	48.2
Plagioclase (Oligoclase)	23.2
Biotite	5.6
Apatite	tr
Opaque minerals	tr

(25) Sullivan quarry, Rockdale, Massachusetts, 2 miles northeast of New Bedford. Biotite-muscovite granite gneiss. A 2-inch pegmatite, with prominent branching and sharp contacts, consisting primarily of black quartz and pink feldspar.

MODAL ANALYSIS OF GRANITE

Quartz	54.8
Ortholase	37.0
Plagioclase (Oligoclase-Andesine)	3.3
Muscovite	4.2
Biotite	0.2

REFERENCES CITED

Bray, J. M. (1942) *Spectrographic distribution of minor elements in igneous rocks from Jamestown, Colorado,* Geol. Soc. Am., Bull., vol. 53, p. 765-814.

Brode, W. R. (1939) *Chemical spectroscopy,* John Wiley, 494 pages.

Dale, T. N. (1911) *Supplementary notes on the commercial granites of Massachusetts,* U. S. Geol Survey, Bull. 470, p. 240-288.

——— (1923) *The commercial granites of New England,* U. S. Geol. Survey, Bull. 738, 488 pages.

Fersmann, A. (1931) *Uber die Geochemisch-Genetische Klassifikation der Granit-pegmatite,* Tschermak's Miner. und Petr. Mitt., vol. 41, p. 64-83.

Fitch, A. A. (1930) *Spectrum analysis in Mineralogy,* Adam Hilger Ltd., 52 pages.

Goldschmidt, V. M. (1933) *Elemente und Minerale pegmatischer Gesteine* Ges Wiss. zu Göttingen Math-Phys. Klasse Nachr., (3), p. 370-378.

——— (1937) *The principles of distribution of chemical elements in minerals and rocks,* Jour. Chem. Soc (London), p. 661.

Hess, F. L. (1925) *The natural history of the pegmatites,* Eng. Min. Jour., vol. 120, p. 289-298.

Hitchen, C. S. (1935) *The pegmatites of Fitchburg, Mass.,* Am. Mineral., vol. 20, p. 1-24.

Kemp, J. F. (1924) *The pegmatites,* Econ. Geol., vol. 19, p. 697-723.

Landes, K. K. (1933) *Origin and classification of pegmatites,* Am. Mineral., vol. 18, p. 33-56; 95-103.

Meggers, W. F.; Kiess, C. C.; and Stimson, F. J. (1922-1923) *Practical spectrographic analysis,* Bur. Stand. Sci. Papers, vol. 18, p. 235-256.

Schaller, W. T. (1933) *Pegmatites* in *Ore deposits of the Western States* (Lindgren Volume), p. 144-151.

Strock, L. W. (1936) *Spectrum analysis with the carbon arc cathode layer,* Adam Hilger Ltd., 56 pages.

Van Aubel, R. (1935) *Sur quelques minerais tantalo-columbifères du Kivu,* Soc. Géol. Belgique, Ann., vol. 58, pub. rel. Congo Belge, p. C38-41.

Van Tongeren, W. (1938) *Contributions to the knowledge of the chemical composition of the earth's crust in the East Indian Archipelago,* Pt. 1. *The spectrographic determination of the elements according to arc methods in the range of 3600-5000A;* Pt. 2. *On the occurrence of rarer elements in the Netherlands East Indies,* Amsterdam, 181 pages.

42 Cottage Street, Hingham, Mass.

Manuscript received by the Secretary of the Society, July 27, 1942.

FIGURE 1. LEDGES OF MARTINSBURG
Bed of Susquehanna River, above Harrisburg

FIGURE 2. SPITZENBERG (middle distance) AND SHOCHARY RIDGE (left background)

FIGURE 3. VERTICAL TUBES IN JUNIATA RED SANDSTONE
Cumberland County

ORDOVICIAN CLASTIC ROCKS

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 54, PP. 1067-1122, 11 PLS., 6 FIGS. AUGUST 1, 1943

ORDOVICIAN CLASTIC SEDIMENTARY ROCKS IN PENNSYLVANIA

BY BRADFORD WILLARD

CONTENTS

	Page
Abstract	1068
Introduction	1068
Ordovician clastics	1069
Martinsburg group	1069
General statement	1069
Distribution	1069
Type locality	1069
Topographic expression	1071
Lithology	1071
Historical sketch	1075
Martinsburg equivalents in New Jersey and New York	1082
Ordovician clastics other than Martinsburg group	1083
General considerations	1083
Reedsville shale	1083
Juniata and Bald Eagle beds	1084
Metamorphism of the Martinsburg	1087
Igneous rocks associated with the Martinsburg	1088
Relative ages and correlations	1088
Stratigraphic relations	1088
Paleontologic evidence of age	1091
Geologic structures	1106
Slatington area	1106
Lynnport area	1110
West of Lehigh County	1113
Sedimentary sequence	1114
Paleozoic cycles	1114
Ordovician sequence	1115
Taconic disturbance	1117
Summary	1118
References cited	1118

ILLUSTRATIONS

Figure	Page
1. Sketch map showing distribution of Ordovician clastic sedimentary rocks in Pennsylvania	1072
2. Comparative sections in Lehigh and Berks Counties	1108
3. Sketch map of region from Slatington westward	1109
4. Sketch map of Mosserville-New Tripoli area	1110
5. Sketch map of northwestern Lehigh County	1111

Figure Page

6. Generalized north-south sections from Lehigh County to the Susquehanna River 1113
7. Diagram illustrating cyclic Paleozoic sequences of facies shifts 1114
8. Diagram illustrating Cambro-Ordovician sequence and facies shifts 1116

Plate Facing page

1. Ordovician clastic rocks 1067
2. Bald Eagle sandstone 1070
3. Martinsburg group 1071
4. Sheared Martinsburg 1074
5. Sandstone and chip conglomerate 1075
6. Martinsburg group 1076
7. Limestone in Martinsburg group 1077
8. Interbedded platy limestone 1082
9. Martinsburg group 1083
10. Contacts 1088
11. Contacts 1089

ABSTRACT

The chief expression of Ordovician clastic sediments in Pennsylvania is the Martinsburg group which forms a broad band from the east-central to south-central border. In central Pennsylvania is an isolated area of Reedsville shale. The Bald Eagle conglomerate and sandstone and the Juniata red beds, younger than the Martinsburg and Reedsville, have a wide distribution in central and south-central Pennsylvania. Fossils, age of subjacent and superjacent beds, and other data delimit the Ordovician clastics. The Martinsburg consists of a lower, shaly part (slaty in east) whose age ranges from early Trenton through Eden. Above, the shale may pass into sandstone of early Maysville (Pulaski) age. Locally, the Jonestown red beds, Eden and younger, are continental equivalents of the marine Martinsburg with which they intergrade. Structures, stratigraphy, and paleontology indicate that the marine Martinsburg is twofold: shale below sandstone, not threefold: shale, sandstone, shale, as sometimes stated. The Reedsville is less arenaceous than the Martinsburg and ranges from late Trenton into early Maysville. The Bald Eagle and Juniata are of Maysville-Richmond age. The Martinsburg has a maximum thickness between 3000 and 4000 feet, the Reedsville about 1500, the Bald Eagle and Juniata each range from zero to 1000 or 1500 feet. Fossils are fairly abundant in the Martinsburg and Reedsville but absent from the other units. Metamorphism has altered the shaly, lower Martinsburg in the east into commercial slate. Local, basic, igneous intrusives cut the Martinsburg. The Taconic Disturbance affected the Martinsburg from the Susquehanna Valley eastward, but not the other Ordovician clastic beds. This tectonic interval can therefore be dated post-Pulaski but pre-Richmond. Since it did not come at the close of the Ordovician, it may not be precisely the chronologic correlate of the Taconic Disturbance of New York. The Martinsburg and Reedsville together represent the offlap phase of the Cambro-Ordovician sedimentary cycle, but the record of terminal events is lost due to Taconic folding and succeeding erosion. The Bald Eagle and Juniata are stratigraphically, structurally, and in provenance distinct from the normal cyclic sequence.

INTRODUCTION

Ordovician stratigraphy in Pennsylvania has received scant attention as a whole, although searchingly studied locally. The system consists of limestone overlain by clastics. Shales locally are altered to slate. This account treats only the clastic sediments.

The writer has for some years studied the Ordovician clastic sediments in the State. Particular attention was given Berks and Lehigh Counties during the 1939 and 1940 field seasons in preparing a chapter on the Martinsburg group of Lehigh County (Miller *et al.*, 1941). Emphasis is placed upon the clastics in Lehigh County because this area is a crucial region connecting areas of altered and unaltered Ordovician.

This distribution of the younger Ordovician units in Pennsylvania is indicated in Figure 1. Table 1 lists the sequences of the Ordovician clastics from Pennsylvania and adjacent areas.

ORDOVICIAN CLASTICS

MARTINSBURG GROUP

General statement.—In Pennsylvania the Martinsburg group ("formation" of most writers) is the dominant Ordovician clastic sequence. The group as here used includes the Fairview and Shochary sandstones and several other units.[1] Therefore, Martinsburg *group* is preferable to *formation* (Willard, 1939). Distinct from the underlying Martinsburg and its sandstones are the Juniata and Bald Eagle beds, of whose Ordovician age there is little doubt. The red Juniata is a correlative of the Queenston red shale of New York. Willard and Cleaves (1939) proposed that the Bald Eagle conglomerate and sandstone be considered the basal member of the Juniata; they believe the Bald Eagle is at least partly Richmond in age, not all Oswego as reported by some authors.

Distribution.—The Martinsburg (*sensu stricto,* excluding the Reedsville) crosses Pennsylvania from the east-central border to the south-central border of the State. There are a few unimportant outliers. In central Pennsylvania, chiefly in Centre, Clinton, and adjacent counties south and east is an area of older Paleozoic rocks which includes Ordovician clastics. The oldest, the Reedsville shale, closely resembles the Martinsburg but is less sandy, lacks red beds and the peculiar thin limestones found in the eastern Martinsburg, and its base is younger.

The Martinsburg or equivalent beds cross New Jersey into New York along the Hudson River Valley. Southward, the Martinsburg crosses Maryland into West Virginia and Virginia.

Type locality.—The Martinsburg was first named "Martinsburg shale" by Geiger and Keith (Wilmarth, 1938) but only a few general remarks

[1] Other units are the Jonestown red beds and certain local limestones, conglomerates, etc. The name Dauphin is proposed for the lower, shaly portion of the group. This name is taken from Dauphin County within whose borders are many excellent exposures and sections of the lower Martinsburg.

TABLE 1.—*Ordovician-Silurian sequences in Pennsylvania and near-by States*

	Maryland and South-Central Penna.	Central Penna.	Susquehanna Valley	Lebanon County	Lehigh County	Northern N. J.	N. and N. W., N. Y.
Silurian	Clinton Tuscarora	Clinton Tuscarora	Clinton Tuscarora	Clinton Tuscarora	Clinton Tuscarora	Shawangunk	Clinton Medina
Ordovician	Juniata	Juniata	Juniata				Queenston
	Bald Eagle	Bald Eagle	Bald Eagle	Bald Eagle	Bald Eagle		Oswego
	Upper Martinsburg or Fairview	Upper Reedsville	Upper Martinsburg or Shochary	Upper Martinsburg or Shochary	Upper Martinsburg or Shochary	Upper Martinsburg	Pulaski Frankfort
	Lower Martinsburg	Lower Reedsville	Lower Martinsburg or Dauphin	Lower Martinsburg or Dauphin	Lower Martinsburg or Dauphin	Lower Martinsburg or "Utica"	Utica
	Chambersburg	Trenton	Chambersburg	Beekmantown ?	Jacksonburg	Jacksonburg	Trenton

FIGURE 1. MANNS NARROWS, JACKS MOUNTAIN

FIGURE 2. TYRONE

BALD EAGLE SANDSTONE

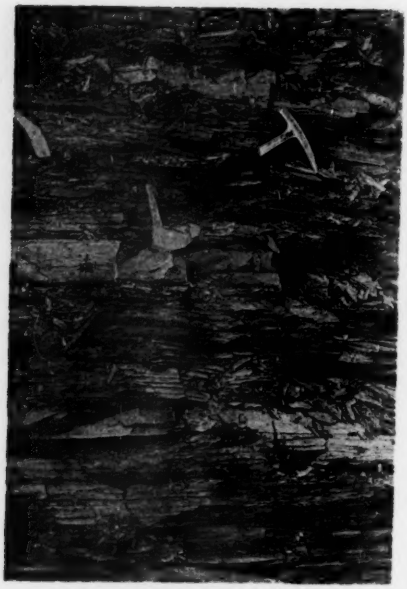


FIGURE 1. SANDY MARTINSBURG
South of Slatington. Interbedded shale.

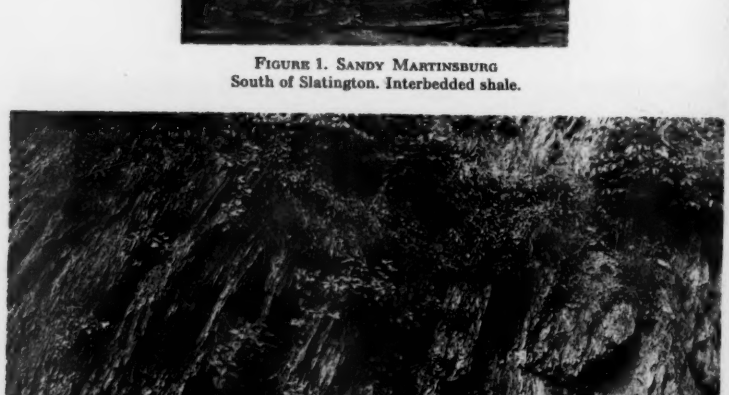


FIGURE 2. LOWER MARTINSBURG
Limestone inclusions, Lemoyne.

MARTINSBURG GROUP

appeared. In 1894, Keith published the first adequate description as follows:

"This formation occurs only in one belt in this area—near the center of the Shenandoah Valley. Martinsburg, West Virginia, is situated on the western edge of this belt and gives its name to the formation. It consists of black and gray calcareous and argillaceous shales of fine grain, and shows no variations within this area. It contains 80 per cent of argillaceous and siliceous matter, and the remainder is chiefly carbonate of lime."

Keith assigned a thickness between 700 and 1000 feet, the top eroded, the base resting upon the Shenandoah limestone. Correlation was suggested with the Hudson River and Utica shales.

Topographic expression.—In general the Martinsburg group forms low, rolling hills. The sandstones of the group in south-central Pennsylvania are poor ridgemakers. Commonly they contain calcareous cement and break down readily. Thus, the massive sandstones in Wildwood Park in the northern end of Harrisburg are scarcely noticeable as topographic features, though small hills occur on the west bank of the Susquehanna above Harrisburg. The sandstone may appear as ledges in the river (Pl. 1, fig. 1). A conglomerate called Paxton Creek (Willard and Cleaves, 1938) supports Reservoir Hill in Harrisburg and is exceptional. In northeastern Berks and northwestern Lehigh counties sandstones of the Martinsburg are pronounced ridge makers. The most prominent is Shochary Ridge (Pl. 1, fig. 2), which reaches a maximum elevation of over 1060 feet in Lehigh County. At its contact with the underlying limestone to the south, the Martinsburg has locally been metamorphosed to a more resistant rock. Under such conditions a small ridge may develop. Thus, at Hershey, the Hershey Hotel is located on this type of hill.

Lithology.—Behre (1933, p. 136) has described the lithology of the Slate Belt as follows:

"For practical purposes, the formation is best subdivided on a lithologic basis into a lower, middle, and an upper part. The lower part is characteristically a banded clay slate, though there are also thin sandstone beds. The middle member contains sandy beds as its most typical facies, though some truly slaty beds are also found in it. The uppermost member is banded like the lower, but there is less sand and the individual beds are much thicker. The differences between these subdivisions are relative and in areal mapping the line between them is drawn with difficulty."

Some new data have been accumulated on the sandstone called Shochary by Willard and Cleaves (1939) from the type locality, Shochary Ridge of Lehigh County, where it is about 750 feet thick. The upper 150 to 200 feet, unlike the lower part, are essentially noncalcareous and

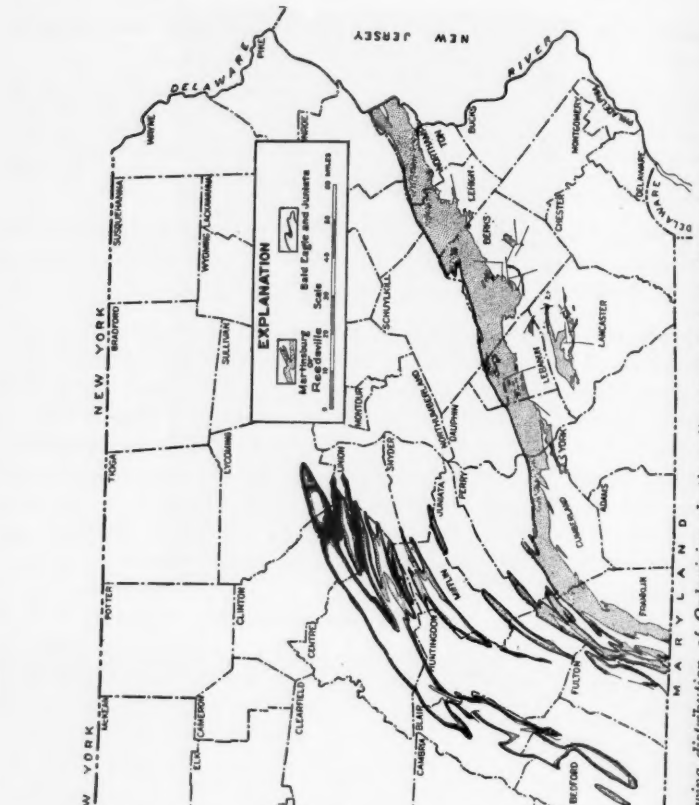


FIGURE 1.—*Sketch map showing distribution of Ordovician clastic sedimentary rocks in Pennsylvania*

so betray their presence topographically.[2] Throughout, the sandstone is medium- to fine-grained, well-sorted, even-bedded, arkosic. Conglomeratic beds are rare. Beds of sandstone up to 4 feet thick occur, exemplified in cuts on U. S. Highway 22, west from New Smithville, Lehigh and Berks counties, and along the Lehigh River south from Slatington, Lehigh County (Pl. 5, figs. 1, 2). When fresh, they are commonly dark gray to gray brown. They weather darker or rusty to buff. The soil over a weathered outcrop is often full of small fragments of sandstone, which may be quite fossiliferous.

There is no sharp line of separation between the sandstone and the shaly or slaty beds, although the contact may be topographically evident. Interbedded with the Shochary are certain minor variations, the most noticeable being conglomerates of three kinds, limestone, quartz pebble, and what is here called chip conglomerate.

Some of the conglomerates are composed chiefly of pieces of limestone and a few sandstone phenoclasts plus shale fragments, all enclosed in an impure, sandy matrix.[3] The limestone pebbles are subangular, dark gray, weather lighter, and effervesce in cold, dilute hydrochloric acid. They occur in beds 2 to 3 feet thick and apparently are rather widely distributed, particularly in Berks County. They are quite distinct from certain edgewise conglomerates also found as lenses in the Martinsburg associated with small limestone deposits.

Another common calcirudite is the chip conglomerate. It resembles the type just described but is finer. This extraordinary rock consists of a mass of small, subangular chips of limestone and some shale ⅛ to 1 inch in longest dimension, scattered through a sandy or muddy matrix. Ward reports bits of cherty material and quartz pebbles also in this type. On weathered outcrops the rock becomes honeycombed as the limestone phenoclasts weather out. Where the bed is concealed, its presence can be determined by characteristic float fragments. The rock has occasionally been quarried and burned as on the farm of Mr. Elmer Bailey, 1 mile northeast of Wesserville, Berks County (Pl. 5, fig. 3). A road cut north of his house and an abandoned quarry on the hill to the east show the

[2] This interpretation of the sandy eastern Martinsburg is not strictly in agreement with the suggestions made by Ward (1936; 1937). In fact, it is in this only that Ward and the author disagree in the interpretations of the group. Ward believes that the noncalcareous beds with Pulaski fossils are actually older than the calcareous beds. The writer, however, believes that if the Pulaski fauna in the crest of Shochary Ridge belongs in beds older than the sandstones to the south between this ridge and the southern shale belt, the Pulaski fauna should reappear to the south. No trace of such a fauna has been found. On the other hand, a few scattered fossils in the sandstones south of Shochary Ridge indicate that they are of Eden age. Apparently Stose (1930) had some such idea; that is, that the calcareous sandstone overlies the noncalcareous. However, from his sections, it is possible that he considered them more or less contemporaneous in Lehigh County.

[3] Not to be confused with the Spitzenberg conglomerate, a unique deposit near Hamburg, Berks County, and probably of Triassic age.

conglomerate. In the quarry the conglomerate is adjacent to coarse, gray sandstone of the Shochary and some coarse limestone conglomerate including reddish, sandy phenoclasts. The chip conglomerate usually occurs in beds 2 or 3 feet thick, though it may be as much as 6. These beds, locally good key beds, are widely distributed. The author has encountered them from eastern Dauphin County into Lehigh.

Quartz conglomerates or pebbly sandstones occur rarely as restricted lenses. One has been mentioned in Reservoir Hill, Harrisburg. It is composed of ill-sorted, poorly rounded, white quartz pebbles and shale chips about half an inch in diameter in a muddy matrix. It is a lens several feet thick and extending 2 or 3 miles along the strike.

Occasionally, beds of mud chips or shale fragments up to 6 or 8 inches in diameter embedded in mud and sand are found. Some of the fragments may be true clay galls; others are redeposited pieces of shale or mud. Most of the fragments are angular, sorting is poor, transportation must have been limited. Individual lenses may be several feet thick but are too restricted laterally to be of correlative value. One of the finest examples of this type of rock was observed in cuts on the State Highway about one-half a mile southeast of Lynnville, Lehigh County.

Aside from the conglomerates, the most interesting lithologic variant is the red beds, most abundant from Berks County westward. They are few and thin in Lehigh County but crop out on the small ridge about half a mile south of Werleys Corners near the western border of the county. They are more common westward, taking up about 500 feet of the section in Lebanon County, and then disappear shortly after crossing the Susquehanna above Harrisburg. They were named the Jonestown beds (Willard, 1939). Stratigraphically, the Jonestown red beds apparently lie near the base of the sandstones of the eastern Martinsburg and extend down into the underlying shale member. It is not uncommon to find the beds associated with thin limestones (Pl. 6, fig. 2).

Ward reports (1937) certain siliceous shales in the Martinsburg in Berks and Lehigh counties. The rock is harder than the surrounding shale, resembles dark chert when fresh, weathers brown, and breaks up into blocks and lumps. Silicification is irregular. Similar beds are quite common in the Martinsburg from the Schuylkill westward. In the northern shale belt, particularly of Dauphin and Lebanon counties, they are associated with black graptolitic shales. Occasionally several chert beds occur near together and have been worked for road metal as seen in small quarries along U. S. Highway 22.

Limestones are present in the Martinsburg, quite apart from the limestone conglomerates cited. A few beds of coquinite occur as for example on State Highway 100 in Low Hill township, Lehigh County. The more

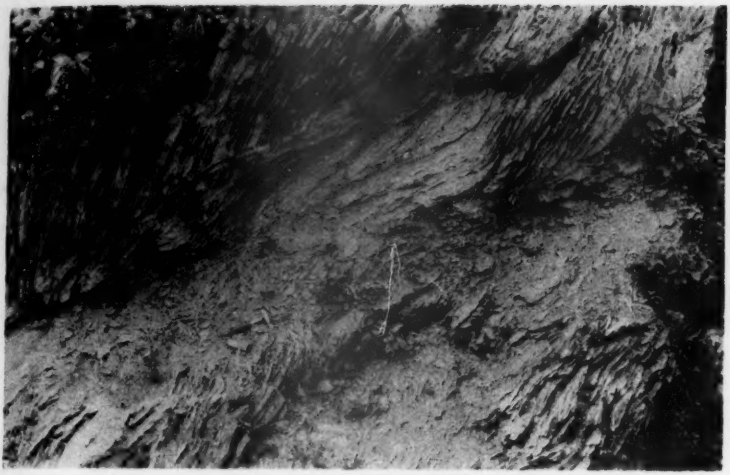


FIGURE 1. FRANKLIN COUNTY
Slaty cleavage not well developed.

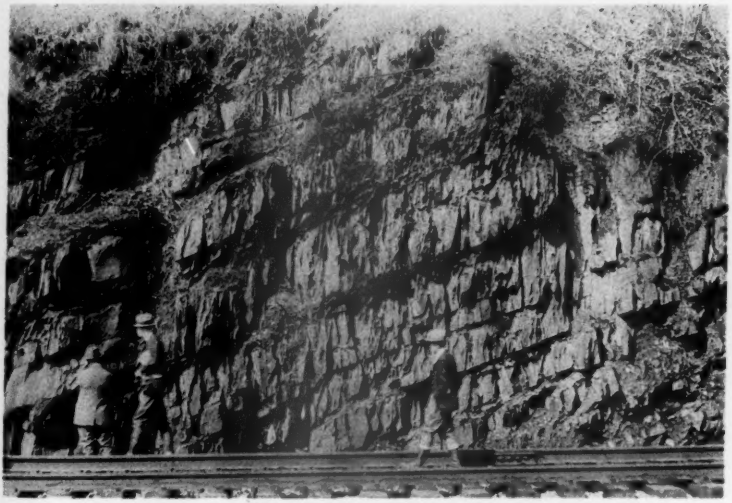


FIGURE 2. NEAR SLATINGTON
Slaty cleavage well developed. Bedding dips gently left.

SHEARED MARTINSBURG

FIGURE 1. MASSIVE MARTINSBURG SANDSTONE
Wildwood Park, Harrisburg.

FIGURE 2. MASSIVE MARTINSBURG SANDSTONE
Highway 22, Lenhartsville.

FIGURE 3. LIMESTONE-SHALE CHIP CONGLOMERATE
Northeastern Berks County.

SANDSTONE AND CHIP CONGLOMERATE

abundant limestones interbedded with the clastic Martinsburg have been described by Ralph L. Miller (1937b) from west of the Susquehanna River eastward into Northampton County. He records four types: (1) most commonly, light-gray, fine-grained, pure stone interbedded with share; (2) less common, 2- to 6-inch beds of limestone separated by shale partings of equal thicknesses; (3) abundant platy beds 1 to 3 inches thick with shale partings. Examples are numerous in the Susquehanna Valley at Harrisburg and across the river, particularly at Enola (Pl. 7, fig. 3; Pl. 8, figs. 1, 2; Pl. 9, figs. 1, 2). Similar beds occur in the Martinsburg in south-central Pennsylvania (Pl. 7, figs. 1, 2). A fourth type is massive to sandy beds 1 to 8 feet thick with occasional shales. Striking, edgewise conglomerates or breccias may be present. West of Lehigh County the limestones are associated with the dark shales and the Jonestown red beds. Upon this association the author recently commented as follows (Willard, 1940):

> "The lithology of the Jonestown beds and their red color point to non-marine conditions of origin, although non-red shales also are present. The red beds are associated also with thin, more or less lenticular limestones which are barren, platy to submassive and which may alternate with shale interbeds. . . . They contain cross-bedded, sandy layers, oölite, and an abundance of limestone breccia or edgewise conglomerate. From neither the limestones nor the associated clastic sediments has any fossil, animal, or vegetable been recorded. However, mud cracks, current ripple marks, and probable rain prints occur. The presumptive evidence is for fresh-water origin of the limestones and associated red beds. Assuming alternate wet and dry seasons, many of the peculiar features of the limestones might be explained as having originated in playa lakes."

Little more need be said of the Martinsburg lithology west of the Susquehanna. Bassler (1919, p. 157) summarizes the sequence for south-central Pennsylvania. Under the topic of Metamorphism will be found comments upon certain phases of the Martinsburg developed by alteration. From the Susquehanna River westward into northern Franklin County, sandstones are relatively unimportant in the Martinsburg group which is largely shale.

Historical sketch.—Studies of the Ordovician shales and sandstones in Pennsylvania go back over a century. Today there are two schools of thought: One holds that the Martinsburg is separable into sandstone above and shale (or slate) below; the other believes a middle sandstone member separates two shale or slate members. These two views will be referred to hereafter as the two-part *vs.* the three-part or the difid *vs.* the trifid schools.

Rogers (1858) gives a detailed description of the rocks now called Martinsburg; he had already (1836; 1838) published some significant remarks on the "slate". He designates (1838) as "Formation III" beds at least 6000 feet thick, lying along the northern side of Kittatinny Valley

and describes them as "dark, fissile slates, usually blue, dark gray, black and dingy olive, and sometimes drab, yellow and red. Contains also some beds of sandstone, and a few of conglomerate". He recognizes the present-day Reedsville shale of central Pennsylvania and apparently believes the workable roofing slate along the southern foot of Kittatinny Mountain occupies the uppermost part of Formation III. In his final report in 1858 (p. 105), Rogers subdivides the Martinsburg as follows [4]:

MATINAL SERIES

MATINAL ARGILLACEOUS LIMESTONE *(Trenton Limestone of New York).*—A dark-blue and bluish-grey, soft, argillaceous limestone alternating near its upper limit with blue calcareous shale. This whole formation is very fossiliferous, being characterized by the *Chaetetes lycoperdon, Leptaena sericea, Bellerophon bilobata, Isotelus gigas* and many other fossils. In Northampton, Mifflin, and Centre counties, it is from 300 to 550 feet thick.

MATINAL BLACK SLATE *(Utica Slate of New York).*—A blackish and dark-blue fissile slate, usually very carbonaceous, distinguished by *Graptolites, Orbiculae,* and other characteristic fossils. It appears in Northampton County and in Kishicoquillas Valley. Its thickness is from 300 to 400 feet.

MATINAL SHALES *(Hudson River Slates of New York).*—Bluish-grey shales and sandy slates containing, especially in their upper portion, many beds of argillaceous sandstone, and some layers of dark-grey siliceous conglomerate. In the western parts of Berks and Lebanon, the formation contains much red and reddish-brown slate, alternating with yellow layers. The middle portion, in certain localities, yields tolerably good roofing slate. It has many characteristic fossils especially a species of *Graptolithus,* of *Heterocrinus,* of *Orbicula,* of *Modiolopsis* and other *Acephala,* and of several *Trilobites.* It contains some species common to it and the Matinal argillaceous limestone. Thickness in Centre County, 1200 (?) feet.

Furthermore, Rogers notes that the "Matinal shale" thins northwestward to probably 1200 feet in Centre County. He records red beds in the lower part of the "upper slate" in Pennsylvania and their association with calcareous beds and was the first geologist to advocate a difid analysis.

The Second Pennsylvania Geological Survey under J. Peter Lesley published several county reports which include discussions of the Martinsburg and Reedsville. That for Lehigh and Northampton counties (Sanders, 1883) uses New York names, Hudson River and Utica. The "formation" is assigned two parts, upper and lower. The more massive upper part underlies more elevated country, specifically Shochary Ridge in Lehigh County. The large and important slate quarries belong in the lower division. In Huntingdon County, White (1885) refers to the

[4] Rogers gave his succession in order from oldest to youngest, therefore the first mentioned unit is the oldest. His parenthetic correlations with the New York sequence are significant.

FIGURE 1. CRUMPLED MARTINSBURG SHALE
Franklin County.

FIGURE 2. PLATY LIMESTONE INTERBEDDED WITH RED SHALE
Jonestown member, Lenhartsville.

FIGURE 3. LIMESTONE IN MARTINSBURG
Harpers Tavern, Dauphin County. Photograph by R. L. Miller.

MARTINSBURG GROUP

FIGURE 1. PLATY LIMESTONE IN MARTINSBURG
Franklin County.

FIGURE 2. TALUS OF PLATY LIMESTONE
Lower Martinsburg, Cumberland County.

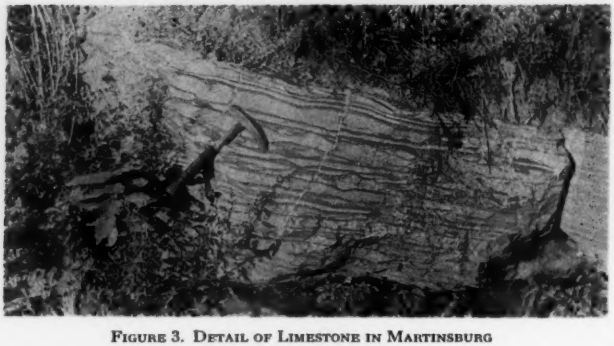


FIGURE 3. DETAIL OF LIMESTONE IN MARTINSBURG
Wildwood Park, Harrisburg.

"Loraine and Utica" shales between 1800 and 2300 feet thick. A. L. Ewing (D'Invilliers, 1884) records "Hudson River and Utica Slate" in Centre County and implies that the upper part is sandy, the lower part slaty. The beds underlie the Oneida (Bald Eagle) and rest upon the Trenton. He lists a few fossils, omits locations and stratigraphic positions. Stevenson (1882) reports in Bedford and Fulton counties 700 feet of "Hudson River" and 200 of "Utica". He mentions occurrence of graptolites. In Blair County, Platt (1881) finds 900 feet of the "Hudson River slates". D'Invilliers (1891) in his account of Union, Snyder, Mifflin, and Juniata counties notes upper alternate layers of sandstone and shale, and lower beds of black "slates".

Lesley (1892) reviews "Formation No. III", the "Utica and Hudson River slates or shales". He believes that the limestone-shale relations below are conformable and represent uninterrupted though changing deposition in the Great Valley. He accepts Rogers' reported thickness of 6000 feet on the Lehigh and Delaware rivers but states that only 700 to 800 feet remains on the West Branch of the Susquehanna and Juniata rivers. Lesley's most significant statement is: "We must remember that the direction of this thinning is across the measures northwestward; and that the great thickness of No. III reasonably maintains itself along the line of strike from northeast to southwest". Lesley subdivides Formation III into two parts; the upper part is dominantly sandy, heavy beds, the lower part thin "mudrock". The sandstones may merge into conglomerates locally. The sandy beds are ridge-making elements in Lehigh County. Lesley, like Rogers, reports red beds in Number III, particularly in Berks, Dauphin, and Lebanon counties.

Dale (1906) observes that workable slate occurs in two belts, one to the north, directly beneath the Silurian of Kittatinny Mountain called "soft vein slate", and one to the south, the "hard vein slate". Dale mentions red strata as far east as Werleys Corner in Lehigh County, farther east than his predecessors had recorded them, and close to the eastward limit recognized today.

Peck (1908) assigns a thickness of perhaps 5000 feet to the "formation". He favors the three subdivisions in that he places the sandstones and graywacks in the middle part.

Use of the name Martinsburg was officially applied in Pennsylvania first by Stose (1910) in the Mercersburg-Chambersburg region. His sequence is:

Upper part: soft sandstone, yellowish-green
Lower part: black, carbonaceous and fissile shale becoming calcareous at base and grading down into the Chambersburg limestone.

Bassler in his 1919 report on the Ordovician and Cambrian of Maryland carries his studies northward into Pennsylvania, more or less overlapping the work of Stose. He records (p. 157) the succession:

Martinsburg shale[5]	Feet
Upper Maysville division.	
Unfossiliferous sandstone (Oswego sandstone). (Probably represented under cover west of North Mountain, in Maryland)	150
Lower Maysville division.	
Fossiliferous gray sandstone with *Orthorhynchula linneyi* bed at top. (Probably present west of North Mountain, in Maryland)	300
Eden division.	
Yellow shale and calcareous sandstone interbedded, with upper Eden fossils	500±
Soft greenish to yellow shaly sandstones and shale with Eden fossils not uncommon at several horizons	500±
Trenton and ? Utica division.	
Dark-gray unfossiliferous shale breaking up into "shoe peg" fragments and often weathering into soft whitish clay	500±
Black carbonaceous fissile unfossiliferous shale	500±
Calcareous dark shale and thin limestone weathering gray containing graptolites (*Corynoides* fauna)	20–100
Granocrystalline fossiliferous limestone and shale holding the *Sinuites* fauna	2–10
Total	2500±

The present Pennsylvania Topographic and Geologic Survey has paid special attention to the economic importance of the slate of eastern Pennsylvania. B. L. Miller's 1925 report on the Allentown quadrangle of southeastern Lehigh and southern Northampton counties embraces the southern border of the Martinsburg. He assigns a thickness of only 3000 feet to the Martinsburg. Assuming that he means the entire Martinsburg, his is the first break from the great thickness recorded by Rogers and accepted by the Second Survey. Miller recognizes three divisions, calls the lowest a succession of shales containing local sandstone and limestone beds, the middle prominent beds of brownish, calcareous sandstone, the upper member shale with a few sandy strata.

Behre (1927) assigns a tripartite character to the "formation". In 1933 he amplifies his 1927 report and discusses the slate for the whole State. The Lehigh-Northampton sequence condensed from his Figure 42 is:

Upper Martinsburg: blue-gray and brownish, widely banded, partly carbonaceous slates and clay shales[6]	2600 feet (?)
Middle Martinsburg: brown, calcareous, locally conglomeratic sandstones and sandy shales with occasional red and green shales; ocherous shales near base. Pulaski fauna at top, Eden at base	4200 feet
Lower Martinsburg: thinly banded clay-slates and slates, and fine-grained, calcareous sandstones; some red beds. Lower Trenton (Upper Black River?) fauna at base	5000 feet

[5] Note that Bassler uses the term Martinsburg in a broader sense than most geologists have used it in that he included the "Oswego sandstone" at the top and limestone at the bottom which could be excluded from the shale facies.

[6] In his 1927 report Behre apparently considered the upper member to be sandier than his 1933 report shows it to be.

Behre's tripartite division is supported by detailed lithologic studies. Observations and chemical analyses of specimens from both hard and soft slates show relatively small differences. They might be used as arguments to show that the two units are correlates.[7] Behre records the astonishing total thickness of 11,800 feet. He shows that his lower Martinsburg member is much like his upper, but sandier. While adhering to the tripartite interpretation, he admits that the bipartite view supported in 1930 by Stose is not impossible.

Behre further supports the tripartite interpretation of the Martinsburg with structural data. In Plate 34, a north-south section (B) across Lehigh County shows the northern slate member overlying the sandy member along their contact. Yet, Behre maps no northern shale remnants atop the sandstone to the south. To the west, where the upper member is said to be absent between the sandy member and the basal Silurian; he suggests that it thins out beneath an unconformity. Behre recognizes the synclinal nature of Shochary Ridge in northwestern Lehigh County and finds it supported by coarse sandstone and some conglomerate assigned to the middle member. In general Behre makes a good case for the threefold interpretation of the Martinsburg in eastern Pennsylvania. He may be designated as the chief exponent of the three-part school of interpretation. B. L. Miller (1939), with slight reservation or changes, appears to accept Behre's trifid interpretation.

The present author in the State Survey report on the Geology of Lehigh County (Miller *et al.*, 1941) has indicated that he adheres to the two-part interpretation of the group. Unpublished reports by Ward (1932; 1934; 1936; 1937; 1939) and Moseley (1938) are in the author's hands. An explanation should be made of the use of Ward's work. Through a misunderstanding, his and the author's field work for the State Survey overlapped between the Lehigh River and the Schuylkill. Each covered at different times this same area. Ward also did considerable work in Northampton County, much of it corroborative of that to the west. West of the Schuylkill he did less detailed work. At a conference, Ward generously offered to turn over his reports, maps, and sections to the author. Professor Ward and the writer are in close agreement on all important points. It is with acknowledgment of his work and appreciation of his generosity that use is made of these data. Though credit may not always be given specifically, Ward has made valuable interpretations of the Martinsburg, particularly in the Slate Belt. Moseley's

[7] Dr. Donald M. Fraser, in an oral communication, stated it as his opinion, after examining Behre's accounts of the minerals in the slates, that the only differences are those produced by higher degrees of alteration of the hard (southern) slate, since it appears that the individual mineral crystals are better oriented in it than in the soft slate.

TABLE 2.—*Summary of interpretations*

	Rogers 1858	Lesley 1892	Weller 1903	Stose 1910	Lewis and Kümmel 1914	Basler 1919	Behre 1933	Willard 1939
Subdivisions	Matinal series							Martinsburg group
	Matinal shale	Upper series	Lorraine	Martinsburg shale	Martinsburg shale	Martinsburg shale	Martinsburg formation	Fairview and Shochary sandstones
	Matinal black slate	Utica & Hudson River slates	Hudson River shale	Upper sandstone	Upper sandy	Oswego sandstone	Upper "soft" slate member	Jonestown red beds
		Lower series	Utica	Lower black shale	Lower shaly	Fairview sandstone	Middle sandy member	Dark shale
						Eden division		
						Trenton and Utica division	Lower "hard" slate member	Cocalico shale
Max. thickness, feet	6000	6000	1165	2000	3000	2500	11,800	4500

work was in part subsidized by the State Survey, and he submitted a brief report and maps on his observations in Hamburg quadrangle. These have been used as a check, and their value is here acknowledged.

Stose (1930) stresses the Martinsburg in southern and south-central Pennsylvania but carries observations in some detail to Lehigh County. He recognizes two members or divisions, a lower shale including thin limestone beds, and an upper, arkosic, sandy member. The shale grades into slate in the east. Stose recognizes Behre's stand on the tripartite interpretation but believes that his upper and lower members are actually the same unit appearing along the northern and southern limbs of a great east-west trending syncline which makes the Martinsburg Slate Belt. Stose produces structural and paleontologic evidence for this synclinal interpretation. He lists Pulaski fossils from high in the sandstone, Eden fossils from older beds. Stose assigns 3000 feet as the maximum thickness for the eastern Martinsburg.

The present author has studied the Martinsburg of Pennsylvania from Maryland northeastward. He has briefly visited localities in New Jersey, New York, Virginia, and West Virginia. Fairly detailed work has been possible as far east as the Lehigh. Northampton County has not been thoroughly investigated because of the available studies by others. The writer believes that the Martinsburg is twofold, shaly beds below sandy beds. Ward agrees with this interpretation. The sandy member lies along a synclinal axis, the shales lateral thereto in the limbs.

The conflicting interpretations appear to be merely a recrudescence of an old difficulty which has beset students of the Paleozoics of Pennsylvania for a century. Those who begin in the more highly metamorphosed, structurally complex east and southeast and progress westward into less altered sections are invariably at a disadvantage as contrasted with those who begin to the west or northwest and pass to the more altered equivalents. Not only are the eastern beds more altered, but they are quite likely to have been of variable or atypical origins as nearshore sediments, while their more remote correlatives deposited farther from shore represent the more nearly "normal" type of sedimentation. If the interpretations of the simpler sequence can be projected into the more complex, many difficulties can be obviated. Of the geologists who have supported the tripartite interpretations, practically all began with the eastern Martinsburg, the Slate Belt. Those supporting the twofold theory have based their interpretation either on a wide field of observations or have learned the unaltered sequence first.

The writer believes that the eastern Martinsburg is between 3000 and 4000 feet thick, more probably nearer 3000. Of this, the upper, sandy

portion, the Shochary, occupies approximately 750 feet. The Reedsville in central Pennsylvania is between 1200 and 1500 feet thick exclusive of the "Oswego" which some authors group with the Martinsburg. In the Susquehanna Valley north of Harrisburg between 2500 and 3000 feet of Martinsburg is recognized. The Jonestown red beds at their maximum, probably in Lebanon County, are about 500 feet thick. Table 2 summarizes the opinions of the several authors reviewed.

MARTINSBURG EQUIVALENTS IN NEW JERSEY AND NEW YORK

Stuart Weller (1903) describes about 1165 feet of Upper Ordovician clastic sediments in New Jersey. He maintains that the slate and underlying "Trenton" (Jacksonburg) limestone are transitional. He remarks that the "Hudson River" slates began to form before the close of deposition of typical Trenton limestones. The lower Hudson River is thus contemporaneous with the Trenton to the west. He questions the precise age of the top of the "Hudson River" formation, yet believes that the slate sequence is the time equivalent of the Lorraine and Utica of New York. Weller divides the beds into lower dark shale and slate with graptolites, upper sandy beds.

The United States Geological Survey folios 161 and 191 on quadrangles in Northern New Jersey record areas of Martinsburg. They divide it as did Weller into an upper and a lower part. The Raritan Folio gives a thickness of 3000 feet. Lewis and Kümmel (1915) summarized the geology of New Jersey. They follow Weller but give a probable thickness of 3000 feet to the Martinsburg. They divide the "formation" into two parts, upper arenaceous beds and lower black shale. Lewis and Kümmel mention transitional Martinsburg-Jacksonburg relations and cite southeastward outliers of Ordovician shales which they call Chazian in age and therefore older than the true Martinsburg. Weller had been noncommittal as to their age.

In a letter of February 1, 1941, Meredith E. Johnson, State Geologist of New Jersey, wrote the author his belief as to the age of the basal Martinsburg:

". . . In the first place the Martinsburg outcrops in a continuous belt in the Great Valley from West Virginia to New Jersey and I am sufficiently familiar with the geology of eastern Pennsylvania and New Jersey to say without hesitation that the strata in these two areas are exactly comparable.

"In the second place, fossiliferous Jacksonburg occurs just beneath the Martinsburg shale in the isolated block of Paleozoics at Clinton just as it does in sections farther to the north and though the Martinsburg in the southerly block contains a much higher percentage of red beds than in the Great Valley, I see no good reason for saying that the shale in the Clinton area is older than that in the Great Valley because Ulrich and Ruedemann say the graptolites are of Normanskill age."

FIGURE 1. IN MARTINSBURG, ENOLA

FIGURE 2. NEARER VIEW OF LIMESTONE SHOWN IN FIGURE 1
Photograph by R. L. Miller

INTERBEDDED PLATY LIMESTONE

FIGURE 1. DETAIL OF LIMESTONE IN MARTINSBURG
At Enola, shown in Plate 8.

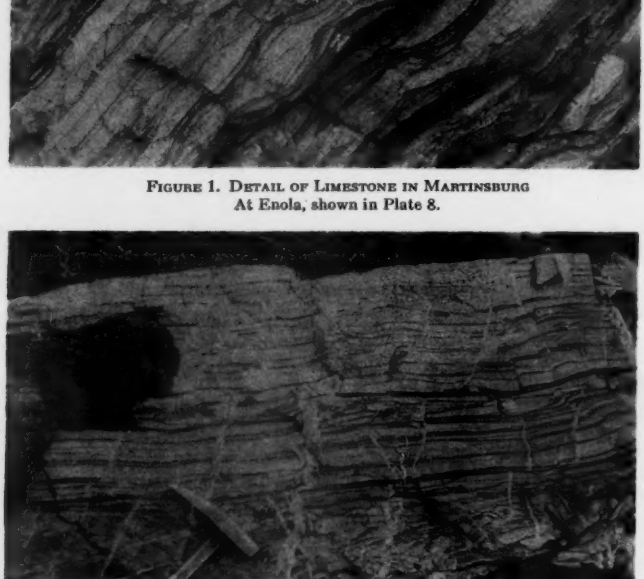


FIGURE 2. DETAIL OF LIMESTONE IN MARTINSBURG
Same as Plate 8. Note thin-bedded material above, brecciated below.

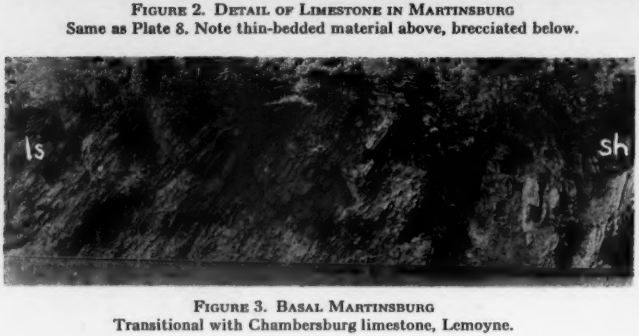


FIGURE 3. BASAL MARTINSBURG
Transitional with Chambersburg limestone, Lemoyne.

MARTINSBURG GROUP

The Upper Ordovician sequence in New York according to Goldring (1931) is:

Lorraine beds
  Pulaski shale
  Frankfort shale
Utica shale
Trenton beds

The highest known Martinsburg fossils correlate with the Pulaski of New York. The base of the oldest Martinsburg is approximately early Trenton. The Utica is characterized as black and gray, argillaceous shale interbedded with gray sandstone, 800 feet thick, containing graptolite zones. The Lorraine beds include the Frankfort, of lithology similar to the Utica, and the Pulaski, alternate gray shales and sandstones. The sandstones weather rusty brown, may be calcareous and have a large and diversified fauna except for the highest beds which are reported as noncalcareous and carrying mainly pelecypods. The similarity of the lithologic and paleontologic succession to the Martinsburg of eastern Pennsylvania is obvious.

ORDOVICIAN CLASTICS OTHER THAN MARTINSBURG GROUP

General considerations.—For distribution, thickness, and economic value, the Martinsburg is the most important Ordovician clastic deposit in Pennsylvania, but others deserve mention. The Reedsville shale is a partial correlate of the Martinsburg. The Juniata red beds and the Bald Eagle are closely related, and the Bald Eagle appears to cover a wide area and be of considerable correlative value. These units are involved in the interpretation of the Taconic Disturbance as it affected Pennsylvania. (*See* Table 1.)

Reedsville shale.[8]—The Reedsville shale of central Pennsylvania has been mentioned briefly. Named by Ulrich in 1911 (Wilmarth, 1938), it was recognized by earlier workers who referred to it along with the Martinsburg under the general heading of "Hudson River". The Reedsville is widely distributed in Centre, Clinton, and adjacent counties. The type locality is at Reedsville, Mifflin County. Recent work by Butts and Moore (1936) on the Bellefont quadrangle and by Butts (1939) on the Tyrone quadrangle are the latest concepts of this formation. The Reedsville rests upon the dark, fine, relatively thin-bedded Trenton limestone among whose fossils Butts lists:

Dalmanella rogata (Sardeson) *Ceraurus pleurexanthemus* Green
Dinorthis pectinella (Emmons) *Cryptolithus tesselatus* Green
Rhynchotrema increbescens (Hall) *Homalonotus (Brongniartia) trentonensis* Simpson

[8] The term "shale" is retained here since that is the dominant lithologic character of the Reedsville.

The Reedsville is overlain by the Bald Eagle ("Oswego" of Butts) sandstone and conglomerate. The Trenton-Reedsville relations are conformable. Generalizing, the Reedsville sequence consists of a basal limy portion 25 or 30 feet thick which is believed to be transitional with the Trenton. Argillaceous shales, more or less sandy and limy, follow, the proportion of sandstone increasing upward into the higher beds. These appear to pass conformably into the Bald Eagle. A thickness of 1500 feet is about the maximum for the Reedsville, although the average, as determined by Butts, is probably nearer 1000. Fossils are not generally abundant. An *Orthorhynchula* zone is usually present near the top. The fauna of the upper beds, Butts suggests, is equivalent to the Eden and Maysville of Ohio and the Lorraine of New York. The graptolites in the lower, shalier part are best correlated with the Utica fauna of New York. Thus, the upper beds appear to equal the sandy, upper Martinsburg (Shochary and Fairview sandstones) of eastern and southern Pennsylvania respectively. In the passage from dark shale below to sandy beds above, the Reedsville resembles the Martinsburg lithologically. Also, both may have thin limestones in the lower part. However, the Reedsville lacks red beds, and its base is not so old as that of the Martinsburg. The Reedsville rests upon limestone correlated with the upper Trenton of New York. The Jacksonburg limestone beneath the Martinsburg of eastern Pennsylvania is nearer middle Trenton, and the Chambersburg limestone beneath the Martinsburg in south-central sections is somewhat older. Both Reedsville and Martinsburg are overlain by beds assigned to the Bald Eagle into which the Reedsville and the Martinsburg in the south grade. East of the Susquehanna the Martinsburg is separated from the Bald Eagle by an unconformity. Hence, the highest, eastern Martinsburg may be older than that to the west and than the Reedsville.

Juniata and Bald Eagle beds.—Most strata of continental facies of the Paleozoic in Pennsylvania may be demonstrated to pass into contemporaneous, marine equivalents. This is particularly true of the Catskill continental facies of the Devonian, Bloomsburg continental facies of the Silurian, and, to a lesser degree, of the Mississippian and Pennsylvanian. There is more than a suggestion of similar conditions involved in the red Jonestown beds of the eastern Martinsburg. The Juniata red beds and the nonred Bald Eagle, as believed by Willard and Cleaves (1939), are dominantly continental. But, unlike most other Paleozoic continental beds in Pennsylvania, they possess within the State no known marine equivalent. This condition resembles the Mauch Chunk red beds underlying the coal measures in the Anthracite Region

which may pinch out to a feather edge rather than pass into marine beds. The Juniata thickens northwestward, contrary to the habits of other Paleozoic red units which thicken eastward or southeastward. Possibly its source lay to the north. Stratigraphers generally agree that the Juniata represents the Queenston red shale of western New York. These anomalies seem to rule out the Juniata and Bald Eagle as representing the continental facies of the Ordovician in Pennsylvania.

If we accept the Richmond as Ordovician, we should review the chronologic position of the Juniata and Bald Eagle. These beds certainly do not fit precisely into the Ordovician sedimentary cycle in Pennsylvania. Furthermore, from the Susquehanna east, they were deposited after the Taconic Disturbance. On tectonic and stratigraphic grounds they may be isolated from the Ordovician, yet they are certainly not younger than Richmond, and, even though they may not conform to the orthodox cycle, these units are transitional below with older Ordovician beds in southern and central Pennsylvania. This entire question has been reviewed by Willard and Cleaves (1939).

The terms Bald Eagle and Juniata came rather recently into use for long-recognized units. Rogers (1858) calls them "Levant gray sandstone" and "Levant red sandstone" in turn, assigning average thicknesses of 325 and 600 feet respectively. Lesley (1892) misapplies New York terms but quotes many sequences in Pennsylvania. In 1909 Grabau named the Bald Eagle from Bald Eagle Mountain in central Pennsylvania (Wilmarth, 1938). Darton in 1896 (Wilmarth, 1938) appears to have named the red beds for their exposures in the Juniata River valley in Pennsylvania. The term has subsequently had wide application.

The Juniata is dominantly red shale and sandstone with occasional gray beds. Below, it merges with the Bald Eagle, massive gray to greenish sandstone and conglomerate with an occasional red bed (Pl. 2, figs. 1, 2). The Juniata reaches a maximum thickness in central areas of about 1600 feet and drops to zero east of the Susquehanna River north of Harrisburg. The Bald Eagle likewise attains a thickness in the central counties of 1500 or 1600 and, like the Juniata, pinches out to zero eastward beyond the Lehigh River (Pl. 11, fig. 3). Both units thin southward into Maryland. Neither the Bald Eagle nor Juniata is known to contain recognizable fossils, but the peculiar lithology of the Bald Eagle aids in its identification and correlation. Vertical tubes of undetermined origin occur locally in the Juniata (Pl. 1, fig. 3). In all known exposures, the sandstone or the matrix of the conglomerate is speckled due to weathering of disseminated iron compounds. Furthermore, the conglomerates in particular are weak. The friable matrix, even when relatively fresh, crumbles under the hammer so that the pebbles readily break out.

The basal relations of the Bald Eagle are significant. Cleaves (Willard and Cleaves, 1939) shows the transitional relations of this with the top of the Martinsburg in tunnels in south-central Pennsylvania. This sequence is also exposed in highway cuts between McConnellsburg and Mercersburg and elsewhere (Pl. 11, fig. 1). At the Susquehanna River the contact is disconformable; 30 feet of Bald Eagle conglomerate is followed by 80 feet of red Juniata. The Bald Eagle rests upon Martinsburg shale with Eden fossils. Eastward, the Juniata drops out, the Tuscarora rests in apparent conformity upon the Bald Eagle, and the latter is in unconformable contact with the Martinsburg, either shaly Eden beds or the younger Shochary sandstone. A remnant of the Bald Eagle is believed to carry through beyond the Lehigh River into Northampton County (Pl. 11, fig 3).[9]

TABLE 3.—*Summary of Juniata, Bald Eagle, Fairview, and Shochary*

	Juniata	Bald Eagle	Fairview or Shochary
Delaware Water Gap	Abs.	Abs.	Abs.
Lehigh Gap, east side	Abs.	35	?
N. W. Lehigh County	Abs.	10+ [1]	750
Schuylkill Gap	Abs.	Abs.	500 [2]
Little Swatara Notch	Abs.	6–7	Abs.
Swatara Gap	Abs.	4–5	Abs.[3]
Heckert Gap	Tr.	?	?
Susquehanna Gap, west	80	30	Abs.[4]
Sterretts Gap	100+	?	Abs.
Doubling Gap	575	Tr.[5]	Abs. ?
E. Blue Mtn. Tunnel	775	148	204
W. Kittatinny Tunnel	774	168	246
E. Tuscarora Tunnel	820	124	135
McConnellsburg-Ft. Louden	400	150	300
McConnellsburg-Mercersburg	400	125	300
Kishacoquillas Gap	1590	300	425[6]
Bellefonte	1000	800	40[6]
Tyrone	1200	900	40[6]

[1] Now concealed through highway construction.
[2] Thickness estimated.
[3] Present on Little Mountain, 2 miles SE.
[4] Present to south.
[5] Present to NW. on Conococheague Mt.
[6] Sandy upper Reedsville.

[9] Miller, Fraser, and Willard (1941) omit the Bald Eagle from the geologic map and the columnar section, and certain north-south sections in Lehigh County. This was done at the request of the senior author of that report and is contrary to the understanding of Willard. Because of this omission, it is necessary to call the reader's attention to the discrepancy in order that he may understand why the Bald Eagle is described as extending into Lehigh and Northampton counties in the present but not in the county report.

The Bald Eagle and Juniata have no appreciable effect upon the topography east of the Susquehanna. Only in central Pennsylvania is their expression important. In this region the Tuscarora sandstone (Lower Silurian) supports the chief mountain ridges, along which a shelf or secondary ridge marks the position of the Bald Eagle conglomerate and sandstone. The intervening depression is underlain by the red Juniata beds. Distinct from the Bald Eagle are the Fairview and Shochary sandstones here treated as part of the Martinsburg. The Shochary occurs in the east, the Fairview in the south-central region.

METAMORPHISM OF THE MARTINSBURG

From its type locality at Martinsburg, West Virginia, well into Pennsylvania, the Martinsburg group as a whole is no more metamorphosed than the rest of the Paleozoic formations (Pl. 6, fig. 1). In the valley of the Susquehanna River a gradual change creeps in, especially along the southern margin of outcrop where shales have been squeezed against competent limestones. Cleavage may obscure the bedding; locally the rock becomes phyllitic (Pl. 4). Graptolites collected south of Harrisburg at Steelton are smeared across the bedding surfaces to three or four times their normal width. Northward, across the strike, with less alteration fossils are better preserved. East along the southern border in Cumberland, Dauphin, and Lebanon counties the alteration of this portion of the Martinsburg suggests an analogy with the Cocalico shale of Lancaster County (Fig. 1). Stose and Jonas (1933) describe the Cocalico as gray or black argillaceous shale with red, purple, or green shales near the base. Thin sandstones may be present, particularly in the higher parts. There is a total of 1000 feet, much of it altered in the same manner as the southern part of the true Martinsburg to the north.

In northwestern Berks County, across the Schuylkill into Lehigh County, there is a further change in the degree of alteration, noticeable in the entire Martinsburg group, but particularly in the shalier portion. Slaty cleavage is commonly developed, producing the workable slates of the eastern counties (Pl. 4, fig. 2). This metamorphism of the eastern Martinsburg shales is in striking contrast to the unaltered younger Paleozoic shales in northeastern Pennsylvania. Among none of these is there any good, commercial slate, although a little unsatisfactory material was once taken from the Marcellus black shale (Middle Devonian). The Martinsburg seems to have suffered either greater compression or more intervals of compression than the overlying formations.

The Taconic Disturbance affected the pre-Bald Eagle formations of eastern Pennsylvania. The portion of the Martinsburg now altered to

slate was squeezed during both Taconic Disturbance and Appalachian Revolution, the younger formations during only the latter. Possibly associated with the interval of metamorphism is an abundance of quartz veins locally in the Martinsburg. They range from a fraction of an inch to 2 feet thick, and occur particularly east of the Susquehanna and along the southern border of the Martinsburg. Since they have not been observed in the Silurian, their date must be early post-Martinsburg.

IGNEOUS ROCKS ASSOCIATED WITH THE MARTINSBURG

In the Bunker Hills and near-by ridges south of Jonestown in central Lebanon County, certain basic sills or flows and dikes are associated with the Martinsburg (Stose and Jonas, 1927; Gordon, 1921). The dikes cut the shales and resemble superficially the basic Triassic rocks to the south but have distinguishing features such as a greenish tint from chloritization while the Triassic rocks have clear, sparkling feldspar. Coarse, volcanic breccia and some beds which may be altered volcanic ash have been observed near Jonestown. The igneous rocks presumably are late Ordovician.[10]

RELATIVE AGES AND CORRELATIONS

STRATIGRAPHIC RELATIONS

The relative ages of the Martinsburg group and other clastic deposits in Pennsylvania are determinable with a degree of certainty. The Martinsburg itself contains diagnostic fossils. The degree of alteration of the group in eastern counties as compared to that of younger formations aligns it with respect to the Taconic Disturbance. (*Cf.* Figure 1 of Plate 6 with Figure 2 of Plate 4.) Correlations of the group in eastern Pennsylvania with the same group in other areas further date it. The following sequences give three widely separated successions of the group and of the Reedsville with the underlying beds:

Central Pennsylvania	South-central Pennsylvania	Eastern Pennsylvania
Reedsville shale	Martinsburg group	Martinsburg group
Trenton group	Chambersburg limestone	Jacksonburg limestone
Coburn limestone	Greencastle member	Beekmantown limestone
Salona limestone	*Christiania* bed	
Black River group	Stones River limestone	
Rodman limestone	Beekmantown limestone	
Lowville limestone		
Pamelia limestone		
Carlim limestone		
Beekmantown group		

[10] In 1936 W. D. Urry reported on some of the intrusives associated with the Martinsburg. It is not certain from his account which type of igneous rock he studied, whether from dikes cutting the Martinsburg or from a "flow" presumably at its base. The age given is 375± 15, 335± 15. This seems low for an Ordovician rock. If, however, the samples were from the dikes, it is not impossible that they are post-Ordovician possibly Devonian.

FIGURE 1. TRANSITION BETWEEN MARTINSBURG SHALE AND CHAMBERSBURG LIMESTONE
Lemoyne. *See* Figure 3 of Plate 9. Photograph by R. L. Miller

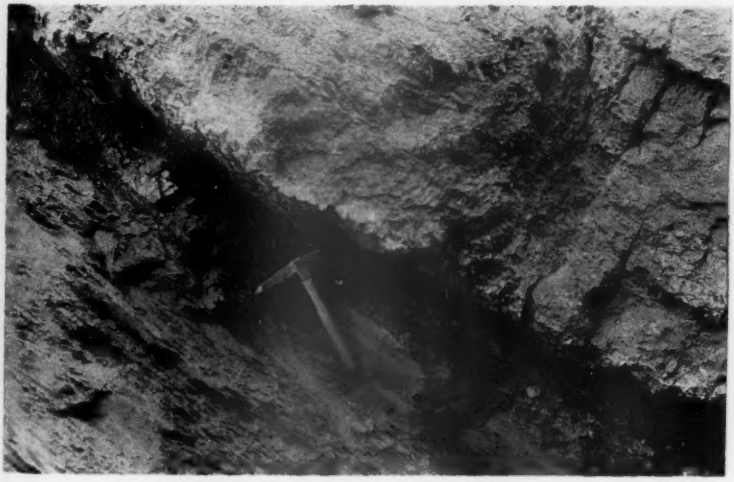


FIGURE 2. MARTINSBURG-SHAWANGUNK CONTACT
Otisville, New York. Note absence of Bald Eagle.

CONTACTS

FIGURE 1. TRANSITIONAL SEQUENCE
Martinsburg (Om), Bald Eagle (Obe), Juniata (Oj), highway east of McConnelsburg.

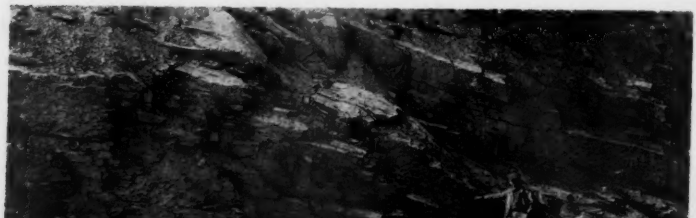


FIGURE 2. TUSCARORA WHITE SANDSTONE (right) IN CONTACT WITH JUNIATA RED SANDSTONE.
Sterretts Gap.

FIGURE 3. MARTINSBURG-BALD EAGLE CONTACT
Lehigh Gap east. Arrow marks contact. Photograph by G. H. Ashley.

CONTACTS

In central Pennsylvania the basal Reedsville overlying the Coburn limestone was deposited at or near the close of Trenton time. From south-central Pennsylvania to the Susquehanna River, the Martinsburg is transitional with the Chambersburg limestone (Pl. 3, fig. 2; Pl. 9, fig. 3; Pl. 10, fig. 1). The upper part of the Chambersburg (sometimes called the Greencastle) may be very late Black River or early Trenton. Immediately east of the Susquehanna River the Martinsburg is in fault contact with the Beekmantown in Paxtang Park, Harrisburg. Here and immediately eastward the Harrisburg axis (Willard, 1941) caused abnormalities. The Leesport limestone at the base of the Martinsburg in the Schuylkill Valley is of little chronologic value as it is barren. The Jacksonburg limestone of sections farther east is important chronologically. R. L. Miller (1937b) mapped this limestone from New Jersey across Northampton County into Lehigh County. It may extend farther. From fairly fossiliferous eastern exposures, Miller calls the Jacksonburg a probable correlative of the Sherman Fall of New York middle Trenton.

In summation, the basal, eastern Martinsburg overlies beds older than does the base of the Reedsville in central Pennsylvania, but in turn rests upon younger beds than the underlying Chambersburg of south-central sections. In the south, the Martinsburg and Chambersburg are transitional, and the basal Reedsville is also transitional downwards. Weller (1903) reports conformity in New Jersey and believes that the Martinsburg is not sharply separated from the underlying limestone. However, R. L. Miller (p. 1701-1702, 1708-1709) observes that the Jacksonburg is disconformably overlain by the Martinsburg near Hackettstown, New Jersey, although the hiatus is chronologically small. Miller records two exposures of Martinsburg-Jacksonburg contact in Northampton County. One is evidently faulted. At the other a local, angular divergence passes into a disconformity. From this and certain near-contacts, it appears that a hiatus probably exists between the shale and limestone with a change from limestone to clastic sedimentation. The time represented is problematic.

Beds next above the Martinsburg in Pennsylvania are not necessarily fully synchronous throughout nor assigned everywhere to the same unit. In northern New Jersey and at Otisville, New York (Pl. 10, fig. 2), the Martinsburg is unconformably overlain by the Shawangunk formation. The contact is hidden at Delaware Water Gap. Continuing west to Lehigh Gap (Pl. 11, fig. 3), the lower Shawangunk or Tuscarora in a cut on the Lehigh and New England Railroad rests upon what Willard and Cleaves (1939) identified as a remnant of the Bald Eagle.

Bald Eagle is exposed at a few localities westward to the Susquehanna. At every contact exposure there is a hiatus between the Bald Eagle and

TABLE 4.—*Age limits of Martinsburg*

			Ohio	Maryland	S.-central Pennsylvania	Susquehanna Valley	Lehigh-Berks Cos.	Delaware Valley	N.-central N. J.	Central N. Y.
Silurian			Brassfield	Tuscarora	Tuscarora	Tuscarora	Tuscarora	Shawangunk	Green Pond	Medina
ORDOVICIAN	CINCINNATIAN	Richmond	Richmond	Juniata	Juniata	Juniata	Disc.		Unc.	Queenston Disc.
		Maysville	McMillan	Bald Eagle	Bald Eagle	Bald Eagle	Bald Eagle			Oswego
						Disc.	Unc.	Unc.		
			Fairview	Fairview*	Fairview*	"Fairview" Jonestown	Shochary** Jonestown	Upper Martinsburg sandstones	Upper Martinsburg (sandy)	Pulaski Lorraine
		Eden	Eden	Lower Martinsburg	Lower Martinsburg or Dauphin shale	Lower Martinsburg or Dauphin shale	Lower Martinsburg or Dauphin shale	Lower Martinsburg shale or slate	Lower Martinsburg (shaly)	Frankfort Utica Lorraine
	MOHAWKIAN		Trenton	Chambersburg	Chambersburg	Chambersburg	Jacksonburg	Jacksonburg	Jacksonburg	Trenton

* *Orthorhynchula* zone present.
** Pulaski fauna at or near top.

the Martinsburg. There is a discordance of a few degrees at Lehigh Gap. On the Schuylkill the Bald Eagle has not been identified. The Martinsburg-Tuscarora contact may be tectonic. At Susquehanna Gap there is a marked lithologic change from Martinsburg shale to Bald Eagle conglomerate without measurable discordance. Still farther west, the Bald Eagle and Martinsburg are transitional in highway tunnels and surface cuts west of and beyond Mercersburg (Pl. 11, figs. 1, 2). In these sections the Fairview sandstone forms the uppermost Martinsburg beds directly beneath the Bald Eagle. In central Pennsylvania the Bald Eagle and the Reedsville are probably always conformable. Because the Bald Eagle thins eastward, it is difficult or impossible to decide whether the eastern remnant represents the entire thickness in central Pennsylvania or its initial, final, or some intermittent stage. The author is rather arbitrarily inclined to view that it reached its maximum distribution early. Subsequent recession accounts for the more restricted geographic distribution of the thickest Bald Eagle and the superjacent Juniata red beds in central and south-central Pennsylvania. Whatever conclusions may be adopted, the actual time discrepancy is relatively small.

The precise age of the Bald Eagle is still open to final proof. Willard and Cleaves (1939 p. 1174) point out that a Bald Eagle-Oswego correlation is unproven. For this reason the term Bald Eagle rather than Oswego should be retained in Pennsylvania. The Bald Eagle cannot be older than the Oswego because of the age and correlation of the youngest Martinsburg (Pulaski) found underneath it in Pennsylvania. It is probably latest Maysville or earliest Richmond. Table 4 gives the ages of the Ordovician clastics.

PALEONTOLOGIC EVIDENCE OF AGE

Paleontologic data from Martinsburg and Reedsville faunas add knowledge of their relative ages. Bassler (1919) finds, at the base of the Martinsburg in Maryland and south-central Pennsylvania, a *Sinuites* bed succeeded by what he calls "the *Corynoides* fauna of Trenton age". He lists a large Eden fauna from the lower or shaly Martinsburg (p. 169) at Jordan Knob, Tuscarora Mountain, and Cowans Gap, Pennsylvania.

In the sandy, upper 300 feet of the Martinsburg, below the "Oswego", Bassler records a zone of *Orthorhynchula linneyi* and assigns it to the lower Maysville or Fairview. Above it are barren beds which may be of upper Maysville age or the correlative of the McMillan of Ohio. From the *Orthorhynchula* bed of southern Pennsylvania, Bassler (p. 170) lists the following faunule:

Lingula nicklesi n. sp.
Plectorthis plicatella (Hall)
Rafinesquina alternata (Emmons)
R. squamula (James)
Orthorhynchula linneyi (James)
Zygospira modesta Hall

Z. ? erratica (Hall)
Ischyrodonta unionoides (Meek)
Pterinea (Caritodens) demissa (Conrad)
Byssonychia radiata (Hall)
B. praecursa Ulrich
Allonychia ovata Ulrich
Modiolopsis modiolaris (Conrad)
Modiolodon truncatus (Hall)
Orthodesma nasutum (Conrad)
Liospira micula (Hall)
Orthoceras lamellosum Hall
Isotelus megistos Locke

Butts and Moore (1936) were unable to find the *Orthorhynchula* zone in the Bellefonte quadrangle, central Pennsylvania, but they reported it in adjacent areas, a statement Butts confirmed in the Tyrone quadrangle (1939). This fossil is present in the upper part of the Reedsville beneath the Bald Eagle ("Oswego") sandstone. Butts (1939) believes most of the Reedsville fossils "occur also in the Lorraine of New York and the Eden and Maysville of Ohio". Graptolites from the basal shale are assigned "to some part of the Utica of New York".

The present author has found no additional paleontologic data on the age of the Reedsville but has collected Martinsburg fossils from many new localities. Stose and others report Martinsburg fossils from several stations. In cuts on State Highway 274, Fannett Township, northern Franklin County, east of Concord and southwest from Hemlocks Forest State Park, fossiliferous, arenaceous shales and thin sandstones relatively high in the Martinsburg are exposed. Because they are separated from the Bald Eagle by a concealed interval, they appear not to be highest Martinsburg. The faunule is:

"Crinoidea," columnals
Bryozoa, undet.
Dalmanella sp. ?
Rafinesquina alternata (Emmons)
Calymene granulosa ? (Foerste)

Of several other faunules obtained in Franklin County, none is known to come from the topmost Martinsburg. All show closer Eden than Maysville affinities.

West of Fort Louden on Township Run, Tuscarora Mountain, east slope, Route 30, near 1540-foot contour, hard, olive shale, probably silicified. Identified by E. A. Brown under author's direction:

"Crinoidea," columnals
Bryozoa, undet.
Dalmanella sp.
Sowerbyella rugosa (Meek)
Rafinesquina squamula (James)
Rhynchotrema sp.
Calymene granulosa (Foerste)

Entrance to gap west of Roxbury, north side of road, in dark, clay shale. Identified by E. A. Brown under author's direction:

"Crinoidea," columnals
Bryozoa, undet.
Dalmanella hamburgensis (Walcott)
D. multisecta (Meek)
Sowerbyella rugosa (Meek)
Rafinesquina squamula (James)
R. alternata (Emmons)
Ischyrodonta unionoides (?) (Meek)
Pelecypoda, undet.
Liospira sp.
Orthoceras sp.
Cryptolithus bellulus (Ulrich)
C. recurvus Ulrich
Calymene granulosa (Foerste)
C. sp.
Trilobite, undet.
Phyllocarid, undet.

Gap west of Upper Strasburg, fossiliferous, dark, hacky shale in upper shaly Martinsburg. Identified by E. A. Brown under author's direction:

"Crinoidea," columnals
Bryozoa, undet.
Dalmanella multisecta (Meek)
Dinorthis sp.
Sowerbyella rugosa (Meek)
Rafinesquina alternata (?) (Emmons)
Zygospira modesta Hall
Byssonychia praecursa Ulrich
Gastropoda, undet.
Orthoceras sp.
Cryptolithus bellulus (Ulrich)
Calymene sp.
Phyllocarid, undet.

The succession east of Concord, Fannett Township, on Highway 274 is significant. Thicknesses are omitted because of concealed intervals. Starting down grade from the crest of Conococheague Mountain the section is:

Tuscarora white sandstone
Tuscarora-Juniata transitional beds, 5 to 8 feet
Juniata red sandstone
Concealed interval
Bald Eagle coarse, olive-gray sandstone and pebble beds
Concealed interval
Martinsburg sandstone, heavy, fossiliferous, with interbedded dark shale

In northern Cumberland County, where State Highway 233 crosses Kittatinny Mountain at Doubling Gap, the stratigraphic succession from the crest south is much the same as at the last place described:

	Feet
Tuscarora white sandstone	
Tuscarora-Juniata transitional beds, alternating white and red sandstones	75
Juniata red sandstone, exposed	400+
Concealed interval, estimated thickness	150–200
Bald Eagle olive sandstone (in gutter)	trace
Concealed interval, thickness indeterminate	
Martinsburg fossiliferous sandstone and interbedded dark shale	

Two faunules were collected here from sandy strata interbedded with shale in the Martinsburg. They may be fairly high in the group but are not from the topmost beds. The lower of these includes:

"Crinoidea" columnals
Climacograptus sp.
Hallopora oncalli sigillaroides(Nicholson)
H. sp.
Plectorthis plicatella (Hall)
Dalmanella multisecta (Meek)
Strophomena sinuata James
Sowerbyella rugosa (Meek)
S. sericea (Sowerby)
Rafinesquina alternata (Emmons)
R. squamula (James)
Zygospira modesta Hall
Byssonychia vera Ulrich
Lophospira lirata Ulrich
Sinuites granistriatus (Ulrich)[11]
Cyrtolites ornatus Conrad
Orthoceras transversum ? Miller
O. sp.
Cryptolithus bellulus (Ulrich)
C. recurvus Ulrich
Calymene granulosa (Foerste)

The second faunule, slightly higher, has been identified by E. A. Brown, checked by the author:

"Crinoidea," columnals
Arthropora sp.
Bryozoa, undet.
Plectorthis plicatella (Hall)
Dalmanella hamburgensis (Walcott)
D. testudinaria (Dalman) var.

Dinorthis (Plaesiomys) subquadrata ? (Hall)
Sowerbyella rugosa (Meek)
Rafinesquina alternata (Emmons)
Zygospira modesta Hall
Cleidophorus planulatus (Conrad)
Hormotoma gracilis (Hall)
Lophospira lirata ? Ulrich
L. sp.
Cyrtolites ornatus Conrad
Sinuites cancellatus (Hall)[11]
S. granistriatus (Ulrich)[11]
Cyclora parvula (Hall)
Gastropoda, undet.
Orthoceras lamellosum ? Hall
Cryptolithus bellulus (Ulrich)
C. sp.
Calymene granulosa (Foerste)
C. senaria Conrad

Sterretts Gap, a wind gap in Kittatinny Mountain, opens from Perry County south into northeastern Cumberland County. Below the foot of the Mountain fossiliferous shaly Martinsburg with a few sandy lenses is exposed in cuts. Because these beds are separated by a long concealed interval from the next highest exposed strata, the Juniata red sandstones, their precise position in the sequence is not known. It is probably somewhat lower than the faunules from the mountain sides in Franklin and Cumberland counties. Fossils were collected and identified by A. B. Cleaves (Willard and Cleaves, 1938, p. 6):

"Crinoidea," columnals
Pholidops cincinnatiensis Hall
Plectorthis plicatella (Hall)
Dalmanella multisecta (Meek)
Sowerbyella sericea (Sowerby)
Leptaena gibbosa (James)
Zygospira modesta Hall
Bilobites ?
Ctenodonta fillistriata Ulrich
Cleidophorus planulatus (Conrad)
Modiolopsis ?
Cryptolithus bellulus (Ulrich)
Calymene sp. ind.
Triarthrus eatoni (Hall)
T. sp. ind.

At the water gap of the Susquehanna River, road cuts along the west side at Kittatinny Mountain completely expose a sequence as follows:

	Feet
Tuscarora white sandstone and conglomerate	275
Juniata red conglomerate and sandstone	80
Bald Eagle gray conglomerate and sandstone	30
Disconformity	
Martinsburg shale, fossiliferous	

The Martinsburg and Bald Eagle are separated by a disconformity. In this section the Fairview sandstone is absent near the gap. It or a correlative sandstone is present 2 miles south. Folding and erosion followed Martinsburg deposition. Subsequent beds therefore rest at one place on the sandstone and at another on the shale. In this particular case, the disconformable contact may well be fortuitous. The top of the Martinsburg at the gap yielded the following faunule:

"Crinoidea," columnals
Bryozoa, undet.
Rafinesquina squamula (James)
Sowerbyella sericea (Sowerby)
Dalmanella multisecta (Meek)
Zygospira modesta Hall
Triarthrus becki Green
Cryptolithus recurvus Ulrich
C. bellulus (Ulrich)

[11] This does not appear to belong to the *Sinuites* bed reported by Bassler from the lower part of the Martinsburg.

East of the Susquehanna River, fossils have been found in the upper Martinsburg. Graptolites occur in the black or dark-gray, lower shales. In the Military Reservation at Indiantown Gap, Dr. P. E. Raymond and the writer discovered a small faunule in thin sandstones among shales exposed along the main east-west street. The beds probably are equivalent to the lower part of the Shochary sandstone, although precise correlation is impossible. This faunule includes:

"Crinoidea," columnals
Rafinesquina squamula (James)
Strophomena sp.
Dalmanella multisecta (Meek)
Zygospira modesta Hall
Ctenodonta sp.
Orthoceras sp.
Ostracoda, undet.

Five miles farther northeast at Swatara Gap, an abundant faunule occurs in dark shales immediately under the Bald Eagle. The stratigraphy suggests that at the Susquehanna; the author has no addition to make to Stose's 1930 list. Stose quotes Ulrich's opinion that the faunule is probably lower Eden:

Diplograptus sp.
Spatiopora lineata Ulrich
Ectenocrinus simplex (Hall)
Heterocrinus sp.
Pholidops cincinnatiensis Hall
Dalmanella emacerata (Hall)
D. multisecta (Meek)
Sowerbyella aff. *sericea* (Sowerby)
S. aff. *plicatella* (Ulrich)
Rafinesquina ulrichi (James)
Leptaena gibbosa (James)
Ctenodonta filistriata Ulrich
Cleidophorus planulatus (Conrad)
Rhytimya producta Ulrich
Colpomya faba (Emmons)
Cuneamya cf. *neglecta* (Meek) (Eden form)
Archinacella patelliformis (Hall)
Sinuites cancellatus (Hall)
Liospira micula (Hall) (Eden var.)
Lophospira ohioensis (James)
Orthoceras aff. *transversum* Miller
Cornulites aff. *flexuosus* (Hall)
Jonesella crepidiformis (Ulrich)
Ceratopsis chambersi (Miller)
Primitia cf. *bivertex* (Ulrich)
Primitiella unicornis (Ulrich)
Elpe radiata (Ulrich)
Cryptolithus bellulus (Ulrich)
C. tesselatus Green (Eden var.)
Calymene granulosa (Foerste)
Triarthrus becki Green (Eden var.)
Tornquistia sp.

If this faunule is lower Eden, it emphasizes the break between the shale and the Bald Eagle. According to Willard and Cleaves (1939) there is a very slight angular discordance here. Yet, at Little Mountain only 2 miles southeast of Swatara Gap, a small outlier of the Tuscarora and Bald Eagle conglomerate overlies nearly vertically upturned beds of Shochary sandstone.

No other important discovery of upper Martinsburg fossils has been made between the Swatara and northeastern Berks County. In northwestern Lehigh County and northeastern Berks, on Shochary Ridge, fossils are quite abundant. Stose lists (1930, p. 648-649) a faunule identified by Ulrich as Pulaski:

Rafinesquina small, aff. *camerata* (Conrad)
R. cf. *alternistriata* Hall and Clarke
R. aff. *ulrichi* (James)
Strophomena n. sp. (coarsely striated like *S. sinuata*)
Sowerbyella aff. *sericea* (Sowerby)
Dalmanella aff. *multisecta* (Meek)
D. sp.
Zygospira modesta Hall

Ctenodonta cf. *levata* (Hall)
Other small pelecypods
Sinuites aff. *cancellatus* (Hall)
Tetranota sp.
Liospira aff. *progne* (Billings)
Lophospira aff. *obliqua* Ulrich
Lepidocoleus jamesi (Hall and Whitfield)
Calymene sp.
Procteus aff. *parviusculus* Hall
Ctenobolbina cf. *ciliata* (Emmons)

Stose remarks that he and Behre jointly collected the material, and Behre (1933, p. 142) lists an essentially similar faunule from the same locality. For comparison with Stose's list, Behre's is quoted:

Zygospira modesta Hall
Dalmanella cf. *multisecta* (Meek)
Sowerbyella sericea (Sowerby)
Hebertella sinuata Hall and Clarke
Plectorthis cf. *plicatella* (Hall)
Rafinesquina aff. *camerata* (Conrad)
R. cf. *alternistriata* Hall and Clarke
R. centrilineata (?) (Hall)
Strophomena spec. nov.
Ctenodonta aff. *levata* (Hall)
Sinuites aff. *cancellatus* (Hall)
Lophospira aff. *obliqua* Ulrich
Tetranota rugosa (Emmons ?)
Liospira aff. *progne* (Billings)
Lepidocoleus jamesi (Hall and Whitfield)
Aparchites (?) sp.
Ctenobolbina ciliata (Emmons)
Calymene sp.
Proetus sp.

The author spent parts of the 1939 and 1940 field seasons searching for additional fossils in Lehigh County. The Pulaski fauna of Shochary Ridge was traced eastward to the valley of Jordan Creek south of Pleasant Corners (Allentown West Quadrangle) and the vicinity of Scherers School. Here the easternmost representative of the Pulaski was found, but the sandstone continues farther east. Outcrops along Jordan Creek furnished the following composite list:

"Crinoidea," columnals
Bryozoa, undet.
Hebertella sinuata Hall and Clarke
Plectorthis plicatella (Hall)
Dalmanella multisecta (Meek)
Sowerbyella rugosa (Meek)
S. sericea (Sowerby)
Rafinesquina alternata (Emmons)
Strophomena sinuata James
Leptaena unicosta ? (Meek and Worthen)
Rhynchotrema sp.
Cleidophorus planulatus (Conrad)
C. sp.
Scenella ?
Orthoceras lamellosum Hall
O. sp.
Ostracod, undet.

For comparison with the foregoing lists from the Shochary sandstone, the following faunule is inserted. It is a composite of several small collections made in the eastern part of the ridge:

"Crinoidea," columnals
Hebertella sinuata Hall and Clarke
Plectorthis plicatella (Hall)
Dalmanella multisecta (Meek)
Strophomena planoconvexa Hall
Sowerbyella rugosa (Meek)
Rafinesquina squamula (?) (James)
Ctenodonta levata (Hall)
Technophorus sp.
Orthodesma nasutum (Conrad)
Pelecypod, undet.
Liospira micula (Hall)
Orthoceras lamellosum Hall
Spiroceras sp.

Fossils have been found in the lower portions of the sandstone down to or into the higher shale beds. Detailed collecting along State Highway 100 from Fogelsville and Jordan Creek northward and thence along Route 29 to the crest of Kittatinny Mountain, traversing northwestern Lehigh County, yielded scattered material. Most of it was collected in

Low Hill and Heidelberg townships, south of Shochary Ridge. The following list is a composite from these places:

"Crinoidea," columnals
Dalmanella multisecta (Meek)
Strophomena sinuata James
S. sp.
Sowerbyella sericea (Sowerby)
Rafinesquina alternata (Emmons)
R. squamula (James)
Zygospira modesta Hall
Lophospira lirata Ulrich
Tetranota ?
Gastropod, undet.
Orthoceras transversum Miller
Calymene granulosa (Foerste)

The Shochary sandstone continues into Northampton County. Immediately east of the Lehigh River the author found a few fragmentary fossils along the road from Slate Valley south toward Treichlers. Their age is dubious. Behre (1933) reports a few fossils from near Point Phillips in what he describes as the lower part of the sandy beds. Ulrich calls them older than Pulaski, perhaps even Trenton. The list was not published. Behre reports no additional Martinsburg fossils from the slate region farther east, nor has Ward or the writer found any in Northampton County, although Ward mentions that fossils have been reported by hearsay in some of the slate quarries. This lack of fossils is not surprising considering the high degree of alteration of the shales and that the sandstones are only partially preserved due to severe erosion of their upper, more fossiliferous portion.

In New Jersey, Martinsburg fossils are scarce. Weller (1903) records a small faunule from a flagstone quarry at Sussex:

Cornulites sp. undet.
Plectambonites sericeus (Sowerby)
Plectorthis plicatella (Hall)
Dalmanella testudinaria (Dalman)

Plectorthis plicatella is recorded from the Maysville and Fairview at Cincinnati, Ohio. Weller reports graptolites at other localities.

The graptolites occurring mostly in the older, shaly Martinsburg raise puzzling questions. Generally these beds are lower in either the three- or twofold interpretation. Bassler (1919) reports a few graptolites from south-central Pennsylvania or adjacent Maryland areas and puts them in the Trenton or Eden. Stose (1910) in the Chambersburg area, reports graptolites from the base of the Martinsburg. He lists (1930) from the Susquehanna Valley north to Harrisburg two graptolite faunules. The fossils had been referred to both Dr. E. O. Ulrich and Dr. Rudolf Ruedemann. They were said to be found 1100 feet below the Juniata. The author was unable surely to reidentify the two horizons in the field. Recent road construction has probably covered both sites. One faunule was determined as characteristic of the Normanskill of the Levis basin:

Didymograptus sagitticaulis Gurley
Dicellograptus sextans (Hall)
Dicranograptus ramosus (Hall) var.
Climacograptus cf. *caudatus* Lapworth
C. modestus Ruedemann
C. parvus Hall
Diplograptus angustifolius (Hall)
Leptobolus walcotti Ruedemann

This identification is sufficiently astonishing considering that the base of the Martinsburg in this section rests upon the Chambersburg limestone which is probably early Trenton. How much more anomalous is the determination by Ulrich of a second faunule from nearly contiguous beds as Deepkill:

Goniograptus aff. *thureaui* (McCoy) (n. sp. ?)
G. perflexilis Ruedemann
Didymograptus extensus (Hall)
D. bifidus (Hall) (large form)
D. cf. *similis* (Hall) and *nitidus* (Hall)
D. cf. *indentus* (Hall)
Tetragraptus quadribrachiatus (Hall)
T. aff. *pendens* Elles (probably n. sp.)
Phyllograptus angustifolius Hall
P. cf. *ilicifolius* Hall
P. cf. *anna* Hall
Dichograptus (?)
Caryocaris curvilatus Gurley

Because of this curious situation, the writer borrowed Stose's collections and submitted them for restudy to Ruedemann. In a letter of May 18, 1938, Dr. Ruedemann wrote as follows:

463 0. Susquehanna Gap, 5 mi. nw. of Harrisburg, Pa. G. W. Stose Coll. Large collection (some labels by Ulrich and Ruedemann, *see* Stose, 1930, p. 641).

Clonograptus flexilis (Hall)
Didymograptus extensus (Hall)
D. patulus (Hall)
C. cf. *indentus* (Hall)
D. bifidus (Hall)
Dicranograptus octobrachiatus (Hall)
Tetragraptus acanthonotus Gurley
T. quadribrachiatus (Hall)
Phyllograptus angustifolius Hall
P. ilicifolius Hall
Caryocaris stosei sp. nov.

It is possible that two horizons of the Deepkill shale are represented in this collection, for *Clonograptus flexilis* occurs in a horizon below the New York Deepkill, and *Didymograptus bifidus* much higher up.

475 W. 445 ft. south of (below) no. 5,[12] south of Harrisburg Gap, Pa. G. W. Stose and A. I. Jonas Coll. 1932.

Didymograptus patulus (Hall)
Tetragraptus cf. *fruiticonus* (Hall), fragment
Caryocaris sp. fragment. Lower Deep Kill

475 W_1. 413 ft. south of (above) no. 5, south of Harrisburg Gap, Pa. G. W. Stose and A. I. Jonas Coll.

Didymograptus cf. *patulus* (Hall), fragment
Tetragraptus (*Etagraptus*) *putillus* sp. nov.
Phyllograptus anna Hall
Crinoid arms, uniserial, narrow
Leptobolus sp. small
Caryocaris curvilatus Gurley. Deep Kill

475 W_2. 53 ft. north of no. 5 (presumably lower 40-50'), south of Harrisburg Gap, Pa. G. W. Stose & A. I. Jonas Coll. 1932.

Worm tubes, no distinct graptolites.

[12] This locality is north of the junction of the new and old highways south of Susquehanna Gap, west side, half a mile south of the Perry-Cumberland County line, Harrisburg quadrangle.

Prior to Ruedemann's restudy of these fossils, he had examined other collections which the author made from the Martinsburg group. They range from the base of the Martinsburg in limy beds transitional with the Chambersburg upward. Most are from west of the Susquehanna; some were obtained east of the River. The lists as determined by Ruedemann are as follows:

Dauphin Co., south edge of Steelton. Basal Martinsburg.

Diplograptus sp. (distorted)
D. (Glyptograptus) euglyphus (Lapworth)
Dicellograptus sp. (branch)
This is probably Normanskill

Dauphin Co., about 2 miles SE. of Manada Gap, Upper Martinsburg shale below flint.

Dicranograptus ramosus (Hall)
Dicellograptus sextans (Hall)
D. gurleyi Lapworth
Diplograptus acutus Elles and Wood
Climacograptus scharenbergi Lapworth
C. parvus Hall
This is undoubtedly Normanskill

Dauphin Co., 1.5 mi. SE. of Oberlin. Basal Martinsburg.

Dicellograptus sextans Hall
Normanskill shale

Franklin Co., E. of Orrstown. Platy ls., transitional between Martinsburg shale and Chambersburg limetone. Poorly preserved.

Diplograptus sp.
Climacograptus scharenbergi Lapworth or *parvus* Hall
Probably Normanskill

Franklin Co., S. of Route 16 on Conococheague Creek. Martinsburg-Chambersburg transition beds.

Climacograptus eximius Ruedemann
Corynoides gracilis Hopkinson
Normanskill-Trenton transition or uppermost Normanskill

Franklin Co., E. of Orrstown.

Platy transitional limestone between Martinsburg and Chambersburg.

Climacograptus cf. eximius Ruedemann
Lasiograptus (Thysanograptus) eucharis (Hall)
Looks like transition zone from Normanskill to Canajoharie

Cumberland Co. ½ mi. SE. of Carlisle Reservoir.

Transition beds between Om. shale and Och. limestone.

Climacograptus strictus Ruedemann
A Canajoharie form

Dauphin Co., quarry at Walnut Run and Manada Creek.

Upper Martinsburg (Dauphin) shale.

Leptograptus ? fragments. Age not determined

During the summer of 1937 Mr. W. M. Laird studied the Martinsburg sequence bed-by-bed along the west bank of the Susquehanna River, supplemented by investigations a mile or two west along the tributary streams. Laird secured additional graptolites which Ruedemann reports on:

Cumberland County, west bank Susquehanna River.

Dicellograptus sextans (Hall)
Diplograptus cf. *angustifolius* (Hall)
Climacograptus parvus Hall
Glossograptus ciliatus Emmons
Retiograptus geinitzianus (Hall)
Undoubted Normanskill

Cumberland County, on road down to creek 1½ miles NW. of Shiremanstown.

Graptolites poorly preserved, weathered
Diplograptus sp. Age uncertain.

Cumberland County, in shale bank north of road bridge across R.R. south of Susquehanna Gap.

Didymograptus sagitticaulis Gurley
Diplograptus cf. *angustifolius* (Hall)
Normanskill

Cumberland County. In new road cut north of road bridge across R.R. south of Susquehanna Gap.
In talus at base of cut in the brown shale.

Climacograptus parvus Hall
Diplograptus euglyphus (Lapworth)
Graptolites poorly preserved. Normanskill

North of Goodville, 1 mile N. of Highspire (collected by Willard).
Graptolites much distorted by folding.
Probably upper Normanskill.

Lebanon Co. South side of large road-metal quarry on Military Reservation, Indiantown (collected by Raymond and Willard).
Poorly preserved.

Leptobolus sp.
Diplograptus sp.
Age not known, possibly Normanskill.

Dr. Ruedemann wrote November 23, 1937, of these faunules: "Practically all are Normanskill forms, a rather unexpected result for Martinsburg shale . . . . . It looks as if the whole collection was done in a Normanskill shale belt." Of the more widely collected faunules, he wrote, May 26, 1937,

"It appears from these lists that some of the supposed Martinsburg shale is undoubtedly Normanskill shale and older than the Martinsburg is usually supposed to be. Some of the shale seems to represent a transition zone from the Normanskill to the Canajoharie or Snake Hill zone (Trenton) that I have not seen here and that would be of great interest to study more closely. There seems to be a mixture there of the last Normanskill and the first Canajoharie forms."

The author's indebtedness and gratitude to Dr. Ruedemann for his painstaking analyses of these faunules is expressed here.

Comparison with New Jersey is interesting since we have no graptolite faunules from the lower Martinsburg of eastern Pennsylvania. Weller (1903) reports as Normanskill a faunule from basal Martinsburg near Branchville:

Diplograptus foliaceus (Murchison)
D. angustifolius (Hall)
Lasiograptus mucronatus (Hall)
Corynoides calicularis Nicholson
Dalmanella testudinaria (Dalman)

From Jutland, near the base of a Martinsburg outlier, he lists additional Normanskill forms:

Climacograptus phyllophorus Gurley
Dicranograptus ramosus (Hall)
Coenograptus gracilis Hall
Reteograptus geinitzianus (Hall)

Much of the lower Martinsburg from the Susquehanna Valley into New Jersey appears from its graptolites to be of Normanskill age except for the Deepkill forms, yet the underlying limestones, where in unbroken sequence, are generally younger. When we include the Deepkill fauna, the situation grows more paradoxical. What explanation seems reasonable? It might be supposed that the Deepkill shale was faulted up among the younger beds, but no structural evidence was seen. Even if movement took place, from whence could such beds be faulted? No Deepkill shale, nor for that matter an appreciable amount of any shale older than the Trenton crops out in the Ordovician of the Susquehanna Valley. That the Beekmantown passes from massive, dolomitic limestone to black shale in 2 or 3 miles is dubious. Peculiar circumstances about which we are ignorant seem to have permitted a few Deepkill graptolites to survive into post-Trenton time.

The occurrence of the Normanskill graptolites can be more readily rationalized. Although they may be chiefly indicative of the pre-Trenton Normanskill shale of New York, some suggest, according to Ruedemann, a transitional stage into the Trenton. The base of the Martinsburg group is older than that of the Reedsville shale of central Pennsylvania. If there were northwestward offlap during deposition of the late Ordovician clastic sediments, such an age relation would be rational. Conceivably, some parts of yet older, but now eroded, sediments which must have extended toward the southeast, were of Normanskill or even greater age.

For convenience in comparison, Table 5 lists the fossils mentioned in this report as found in the Ordovician clastic sediments in Pennsylvania.

TABLE 5.—*Faunal distribution*

	Shochary ss.	Fairview ss.	Dauphin sh. (Eden)	Dauphin sh. ("Normanskill")	Reedsville sh.
Clonograptus flexilis				x	
Dichograptus octobrachiatus				x	
Didymograptus sagitticaulis				x	
D. extensus				x	
D. bifidus				x	
D. patulus				x	
D. similis				x	
D. indentus				x	
Phyllograptus angustifolius				x	
P. ilicifolius				x	
P. anna				x	
Tetragraptus acanthonotus				x	
T. fruticosus				x	
T. putillus				x	
T. quadribrachiatus				x	
T. pendens				x	
Goniograptus thureaui				x	
G. perflexilis				x	
Climacograptus scharenbergi				x	
C. eximius				x	
C. strictus				x	
C. caudatus				x	
C. modestus				x	
C. parvus				x	

TABLE 5.—*Faunal distribution*—Continued

	Shochary ss.	Fairview ss.	Dauphin sh. (Eden)	Dauphin sh. ("Normanskill")	Reedsville sh.
Retiograptus geinitzianus				x	
Dicranograptus ramosus				x	
Dicellograptus gurleyi				x	
D. sextans				x	
Diplograptus (Glyptograptus) euglyphus				x	
D. acutus				x	
D. angustifolius				x	
Glossograptus celiatus				x	
Corynoides gracilis				x	
Lasiograptus (Thynograptus) eucharis				x	
Spotiopora lineata			x		
Hallopora oneilli sigillaroides			x		
Lingula nicklesi		x			
Leptobolus walcotti				x	
Pholidops cincinnatiensis			x		
Rafinesquina alternata		x	x		
R. squamula	x	x	x		
R. ulrichi	x		x		
R. camerata	x				
R. alternistriata	x				
R. centrilineata	x				
Strophomena sinuata	x		x		
S. planoconvexa	x				
S. halli			x		

TABLE 5.—*Faunal distribution*—Continued

	Shochary ss.	Fairview ss.	Dauphin sh. (Eden)	Dauphin sh. ("Normanskill")	Reedsville sh.
Leptaena unicosta	x				
L. gibbosa			x		
Sowerbyella rugosa	x		x		
S. sericea	x		x		
S. plicatella			x		
Plectorthis plicatella	x	x	x		
Dinorthis pectinella					x
D. (Plaesiomys) subquadrata			x		
Hebertella sinuata	x				
Dalmanella rogata					x
D. testudinaria			x		
D. hamburgensis			x		
D. multisecta	x		x		
D. emacerata			x		
Orthorhynchula lineyi		x			x
Rhynchotrema increbescens					x
Zygospira modesta	x	x	x		
Z. erratica		x			
Cuneamya neglecta			x		
Lepidocoleus jamesi	x				
Orthodesma nasutum	x	x			
Ctenodonta fillistriata			x		
C. levata	x				
Cleidophorus planulatus	x		x		

TABLE 5.—*Faunal distribution*—Continued

	Shochary ss.	Fairview ss.	Dauphin sh. (Eden)	Dauphin sh. ("Normanskill")	Reedsville sh.
Ischyrodonta unionoides		x	x		
Pterenia (Caritodens) demissa		x			
Byssonychia radiata		x			
B. praecursa		x	x		
B. vera		x	x		
Modiolopsis modiolaris		x			
Modiolodon truncata		x			
Colpomya faba			x		
Rhytimya producta			x		
Archinacella patelliformis			x		
Cyrtolites ornatus			x		
Sinuites granistriatus			x		
S. canellatus	x		x		
Hormotoma gracilis			x		
Tetranota rugosa	x				
Lophospira lirata			x		
L. obliqua	x				
L. ohioensis			x		
Liospira proque	x				
L. micula	x	x	x		
Cyclora parvula			x		
Orthoceras lamellosum	x	x	x		
O. transversum			x		
Cornulites flexuosus			x		

TABLE 5.—*Faunal distribution*—Continued

	Shochary ss.	Fairview ss.	Dauphin sh. (Eden)	Dauphin sh. ("Normanskill")	Reedsville sh.
Cryptolithus tesselatus			x		x
C. bellulus			x		
C. recurvus			x		
Triarthrus becki			x		
T. eatoni			x		
Isotelus megistos		x			
Proetus parviusculus	x				
Calymene senaria			x		
C. granulosa			x		
Homalonotus (Brongiartia) trentonensis					x
Ceraurus pleurexanthemus					x
Elpe radiata			x		
Primitiella unicornis			x		
Jonesella crepidoformis			x		
Ceratopsis chambersi			x		
Ctenobolbina ciliata	x				
Caryocaris curvilatus				x	
C. stosei				x	
Ectenocrinus simplex			x		

GEOLOGIC STRUCTURES

SLATINGTON AREA

The Slatington area is in northeastern Lehigh County. Behre's reports (1927; 1933), are the most detailed structural accounts. He is at his best in dealing with the slate, less explicit with other parts of the Martinsburg

group. Behre calls attention to the general overturning northward. The major structure is described as monoclinal, interrupted by local folds and small thrust faults. Behre's observations are largely in quarries along the strike of a single, narrow belt. He indicates that the northern slate overlies the sandstones to the south. Conflicting new field evidence bears directly upon this interpretation. If the northern slate overlies the sandstone, the threefold interpretation is probably valid. If the slate underlies the sandstone, its position supports the twofold explanation. Although Behre favors the threefold interpretation, his open-mindedness toward Stose's concept is shown in the following quotation:

"Judging from his detailed work in southern Pennsylvania and from reconnaissance studies in the region here discussed, Stose has interpreted the Martinsburg as comprising only two distinct members—a lower shaly and an upper sandy one—and regards the uppermost, banded, slaty member of Behre as the lowest member repeated by folding. His viewpoint is well supported by field data, but the difference is chiefly one of structural interpretation and hinges upon evidence not as yet available, so that a final settlement is not possible at present. The structural interpretation of Stose is well set forth in a recent publication and that of the writer is given in the maps, structural sections, and local descriptions of this report. . . . If the reader accepts the interpretation of Stose, he should read "lower" where in this report the "uppermost" member of the Martinsburg is referred to.

Figure 2 reproduces some of Behre sections along with others by Stose and the present author. All sections are generalized. Behre, in discussing his sections, comments:

"The most pronounced folds affecting the Martinsburg in this region are two great synclines of the sandy beds of Pulaski age which form respectively Shochary Ridge and the next prominent subparallel ridge of sandstone to the south, which extends eastward from the Pinnacle on Blue Mountain toward Wessnersville. Between these two ridges lies a depressed area, its length extending eastward and its width reaching from Kempton to Trexler. This represents an anticline between the sandstone of the two synclinal ridges mentioned and exposing shaly beds probably corresponding to those immediately north of Shochary Ridge in which, west of Eckville, an Eden fauna was found (as mentioned in the description of the middle member of the Martinsburg)."

All sections in Figure 2 are in general agreement. However, Behre's show the northern shale overlying the sandstone at their contact, the others put sandstone above shale.

Figure 3 shows the region along Trout Creek valley west from Slatington. The sandstone forms the high ground south of the creek which flows over the shale or slate. Many slate quarries pock the area; a few significant ones are shown. Their quoted numbering is that used by Behre.

"Quarry 70", New York Tunnel: An abandoned opening one-quarter mile west of Slatington railroad station is situated at the foot of the sandstone ridge and is cut southward into that hill toward the sandstone-slate contact. A tunnel from the rear of the quarry into the hill

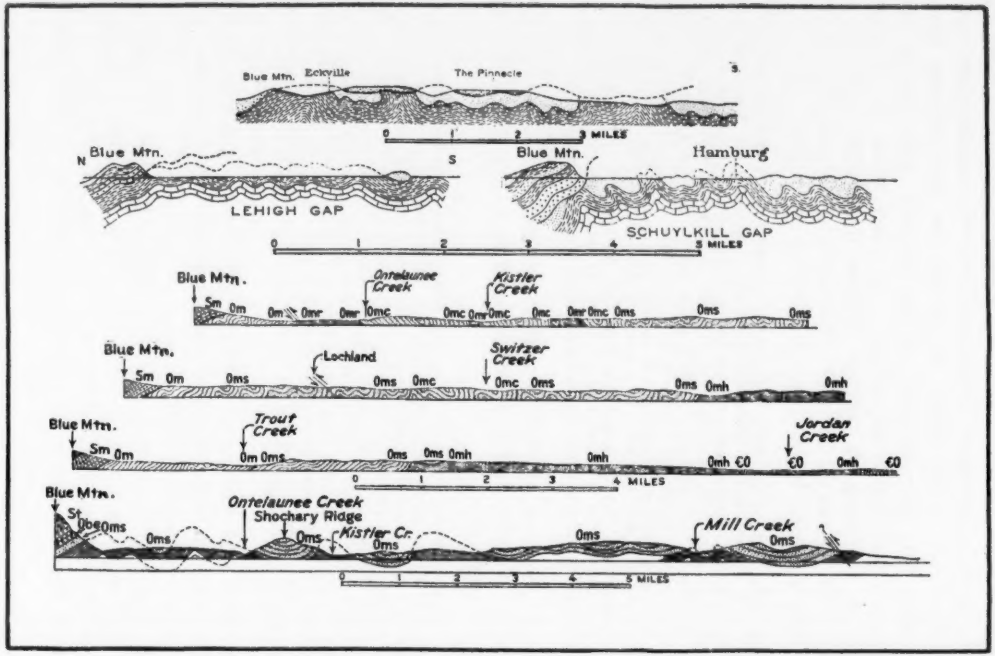


FIGURE 2.—*Comparative sections in Lehigh and Berks Counties*

Upper three after Stose; lowest by Willard partly from Ward; others after Behre. Reprinted from Miller *et al.* (1941).

follows the slate beneath the sandstone. At the tunnel adit the bedding in the slate dips 17° N. along the north limb of an anticline which trends nearly east-west parallel to the hill's axis. Its south-dipping, south limb is exposed just inside the tunnel in the slate at a point almost vertically

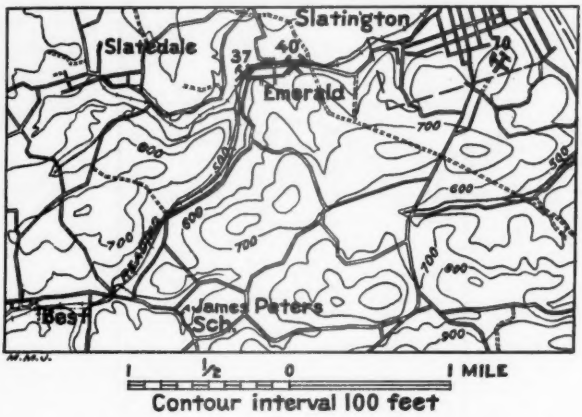


FIGURE 3.—*Sketch map of region from Slatington westward*

beneath the slate-sandstone contact. The slate above the quarry rim dips 46° S. under the sandstone. The author cannot picture the slate overlying the sandstone in normal stratigraphic sequence at this point. If Behre's interpretation is right as to the stratigraphic succession, only a thrust fault, for which no evidence was found, could have brought the sandstone to its present position relative to the slate. Two miles up Trout Creek valley from Slatington is *"Quarry 40", the Emerald Quarry.* The bedding here dips south at the south side of the quarry nearest the sandstone as at the New York Tunnel; this is the south limb of an anticline. Such an attitude should carry the slate beneath the sandstone. *"Quarry 37," of the Ellis Owens Quarries,* west of Emerald, is approximately on the strike of *"Quarry 40."* The beds here dip 70° S. Trout Creek forks at Emerald. The west branch comes in from beyond Slatedale, the south fork descends northward from the sandstone high ground (Fig. 3). Road and railroad cuts, creek banks, and quarries present a complete series of exposures from the slate in the valley into sandstone and most of the way to Best 2 miles south. Arenaceous shale and sandstone of the lower part of the sandstone member have an average strike of N. 80° E., dip 31° S. They pass north above the slate.

LYNNPORT AREA

Behre describes the slate of the Lynnport area in northwest Lehigh County (Figs. 4, 5). He considers the sandstone area north of Mosserville to be anticlinal, the slate (shale) re-entrant to the south, synclinal.

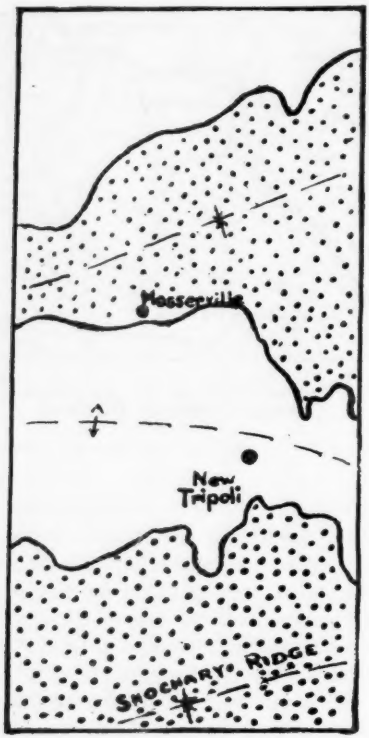


FIGURE 4.—*Sketch map of Mosserville-New Tripoli area*

Northern Lehigh County. Sandstone stippled, shale and slate blank. Scale 1 inch = 1 mile.

He indicates that the slate overlies the sandstone with the slate generally dipping south. In the shale or slate band between Mosserville and New Tripoli, the following faunule, evidently Eden, was collected by the author:

"Crinoidea," columnals
Diplograptus sp.
Rafinesquina squamula (James)
Strophomena hallie (Miller)
Sowerbyella sericea (Sowerby)
Dalmanella multisecta (Meek)

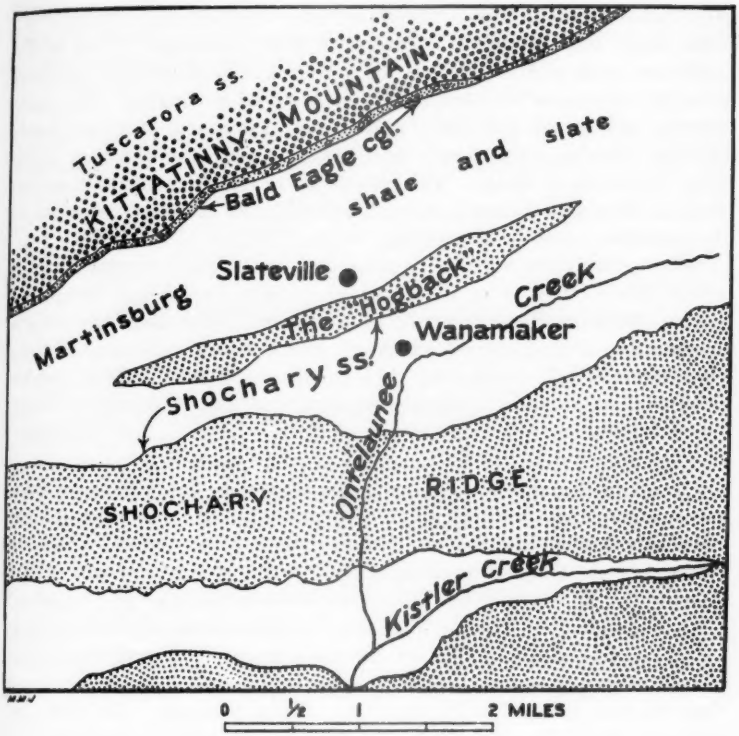


FIGURE 5.—*Sketch map of northwestern Lehigh County*
Showing relative positions of Shochary Ridge and the "hogback". Sandstone stippled, shale and slate blank.

This should be contrasted with the list of Pulaski fossils which the author collected from the crest of Shochary Ridge along the road south of New Tripoli, as follows:

"Crinoidea," columnals
Bryozoa, undet.
Plectorthis plicatella (Hall)
Strophomena sinuata James
Sowerbyella sericea (Sowerby)
Dalmanella multisecta (Meek)
Hebertella sinuata Hall and Clarke
Lepidocoleus plate

All available structural data which the author has collected (Miller *et al.*, 1941, Map) indicate quite the reverse of Behre's findings. That is, the sandstone north of Mosserville is the western end of an eastward-pitching syncline continuous with the sandstone south of Slatington. The shale between Mosserville and New Tripoli is the eastern end of an eastward-pitching anticline whose south limb passes beneath the Shochary sandstone of Shochary Ridge. This sandstone is clearly younger than the shale or slate and merges northeastward with the eastward extension of the sandstone north of Mosserville.

Still farther west, north of Wanamaker, is a narrow sandstone ridge which Behre refers to as the "hogback." (*Cf.* Figure 5.) Behre describes Shochary Ridge south of the "hogback" as structurally, stratigraphically middle Martinsburg. North of it is a slate valley partly along Ontelaunee Creek, separating it from the "hogback." This smaller ridge consists of coarse sandstone suggestive of that in Shochary Ridge, but it is isolated from other sandstone areas. North of the "hogback," another belt of slate has been exposed at many quarries.

The simplest interpretation, as Behre admits, is that the same sandstone forms Shochary Ridge and the "hogback", that it has been brought down in synclines, and that an anticlinal slate valley separates the two ridges. If so, this valley-forming slate would reappear north of the "hogback". However, Behre believes the quarries north of the "hogback" are upper slate and therefore highest of his three-divisional Martinsburg, overlying the sandstone. Since the slate passes below the sandstone of the "hogback" along its northern side, that sandstone must be younger than the slate and cannot be identical with the Shochary. Therefore, he draws a fault along the south side of the "hogback" westward to a re-entrant in Kittatinny Mountain above Eckville.

Independently and with Ward and Moseley, the writer examined a number of sections across the "trace" of the "fault". Ward visited more such localities. We found no unusual conditions pointing to the presence of a large displacement. Furthermore, fossils collected from Behre's "upper slate" a mile northeast and north of the "hogback" and westward are of Eden age.[13] The beds north of the "hogback" should be older than those in Shochary Ridge and likewise than those of the "hogback" if, as the writer believes, those of the "hogback" are identical with those of Shochary Ridge—that is, belong to Shochary sandstone. (*See* Figure 2, lowest section.) The writer found no fossils in the sandstone of the "hogback", but if this is lower Shochary their absence is

[13] Professor Ward submitted his collections from this area to Doctor Ulrich. In a letter of July 14, 1936 to Ward, Ulrich discussed fossils from 14 localities and in every case where the material was identifiable pronounced its age to be Eden, or late Eden, always pre-Fairview.

to be expected. In support of this dissension from Behre's interpretations, Ward believes the south and north slate areas here equal because of lithic peculiarities common to both.

WEST OF LEHIGH COUNTY

From Berks County, especially in the Schuylkill Valley, across Lebanon and Dauphin counties into the Susquehanna Valley, the structure

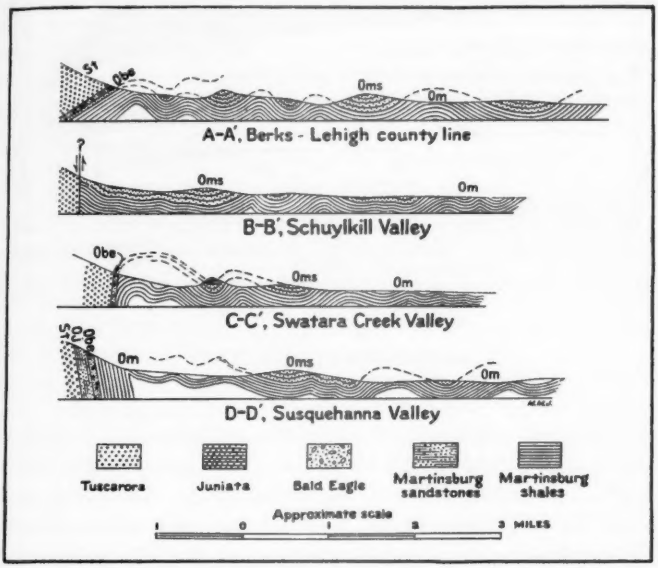


FIGURE 6.—*Generalized north-south sections from Lehigh County to the Susquehanna River*

Thicknesses of Juniata and Bald Eagle exaggerated.

of the Martinsburg is simpler and more easily observed than in Lehigh and Northampton counties. The successions are better and more completely exposed. Continuous sections are fairly common. Key beds and fossils are present and useful. Willard (1939) indicates that this portion of the Martinsburg is a long, narrow synclinorium. Shale, north and south, forms the limbs, with the Jonestown red beds and the Shochary sandstone or a correlate approximately axial, not as a single median band, but as more or less distinct or isolated parallel bands, the axes of minor synclines. Figure 6 shows in general the sandstone-shale relations from Harrisburg to eastern Berks County. Beyond the Susquehanna

Valley, no structural problems were discovered which deserve particular attention. The higher sandstones in general are found along narrow synclines with shale limbs. For typical conditions in south-central Pennsylvania, the reader is referred to Stose (1910).

FIGURE 7.—*Diagram illustrating cyclic Paleozoic sequences of facies shifts* Northwestward across Pennsylvania.

SEDIMENTARY SEQUENCE

PALEOZOIC CYCLES

The Paleozoic systems in Pennsylvania indicate cyclic deposition. Typically, each should begin with marine onlap, attain maximum flooding, perhaps stillstand, followed by marine offlap. The cycles usually culminate in continental sediments which pass into marine westward or northwestward. Interperiodic, orogenic, or tectonic activity is the exception. The cycles best represented in Pennsylvania are Cambro-Ordovician, Silurian, and Devonian. Mississippian and Pennsylvanian (for convenience including the Permian) are less well developed. Each successive cycle transcends its predecessor in that the final continental facies spreads farther west or northwest and at a relatively earlier time in its individual period than its predecessor. (*Cf.* Willard, 1940.) Ordovician continental beds reach only into the middle Susquehanna-Schuylkill valleys. The Silurian continental sequence attains central Pennsylvania; the Devonian "red beds" die out in the northwestern counties of the State. Mississippian fresh-water strata show the beginning of a transition to the marine in southwestern counties. The Pennsylvanian and Permian are represented in the State by little else than continental deposits.

ORDOVICIAN SEQUENCE

The Cambrian and Ordovician systems in Pennsylvania do not resolve into two cycles of deposition but may constitute a single long cycle. We are concerned with the upper or Ordovician portion only. After the close of Beekmantown time which apparently marked the maximum advance of the sea, regression of marine waters is implied by succeeding argillaceous limestones followed by the clastic Martinsburg and Reedsville. Graptolite-bearing, black shales of pelitic-zone genesis in the lower Martinsburg give way to sandy beds and different faunas above. Before sands completely blotted out muds, the Jonestown continental sediments appeared and continued locally at least into later Martinsburg time. The Taconic Disturbance closed Martinsburg deposition but not necessarily Ordovician sedimentation. After an interval of folding and peneplanation, the Bald Eagle followed by the Juniata spread over much of central Pennsylvania. It should be distinctly understood that while the Jonestown beds appear to be the normal continental element of the Ordovician sequence, the Bald Eagle and Juniata are nothing of the sort. Not only are they distinct from the Martinsburg and Reedsville, but their source of material is construed as being essentially north, not south or southeast like other Ordovician clastic deposits.

In recapitulation, the Martinsburg group is the chief expression of clastic Ordovician sedimentation in Pennsylvania. It was deposited in the Appalachian geosyncline, and its materials came from the adjacent landmass, Appalachia, to the south or southeast. The Martinsburg represents successively upward, pelitic and neritic zones. The sandstone and shale show a facies shift in the marine sequence. Contrasting the age of the basal Martinsburg with that of its paracorrelative in central Pennsylvania, the Reedsville shale, the maximum age difference between their basal beds may be nearly the whole of Trenton time. The inference is that offlap was a northwestward transgression of clastic elements over nonclastic limestones. Lithologic changes support this in that the Martinsburg and Reedsville show a shale to sandstone shift northwestward. The Martinsburg in its sandier parts is more arenaceous than the Reedsville, and its sandstones are coarser-grained, less pure, more arkosic, and contain conglomeratic beds. The shift occurs vertically from lower to higher Martinsburg beds and horizontally from Martinsburg to Reedsville.

Such facies changes may occur over short distances. The Mahantango beds (Middle Devonian) in the Susquehanna Valley change from coarse sandstone with conglomerate bands to shale in about 18 miles. Compare these examples with the lithologic differences between the southern

and northern slate belts of Lehigh and Northampton counties. These belts are today separated by 2 to 5 miles but may have originated two or three times farther apart if we recognize crustal shortening. The southern belt is the more sandy. Such a difference, if attributed

FIGURE 8.—*Diagram illustrating Cambro-Ordovician sequence and facies shifts*

Southeastern Pennsylvania. Juniata and Bald Eagle omitted. Ojt = Jonestown red beds, Of = Fairview and Shochary, Omd = Martinsburg (Dauphin) shaly beds, Oj = Jacksonburg, Ob = Beekmantown, Cc = Conococheague (Allentown), Ct = Tomstown, Ch = Hardyston. Partially restored.

to marine regression, fits nicely into the interpretation of a twofold Martinsburg.

Faunal changes conformed to environment. The earlier, dark shale facies is typified by graptolites. Later, the incoming Eden fauna is characterized by small brachiopods, pelecypods, gastropods, orthoceracones, trilobites, pteropods, ostracods, an occasional starfish, bryozoans, and "crinoid" columnals. It is a funa of shallow, benthonic distribution plus planktonic or vagrant forms. The final Pulaski fauna of the Shochary sandstone is generically more restricted than the Eden but contains some larger, thicker-shelled forms suggesting still shallower water.

The Jonestown red beds have been called continental. They are interbedded with barren, brown, gray, and greenish shales and thin, unfossiliferous limestones possessing many peculiarities suggestive of abnormal conditions of deposition, probably fresh-water. Only a little of the Ordovician nonmarine facies is preserved. It encroached from the south or southeast. There were probably still older, now eroded, continental beds toward the source of supply. The outlier of Martins-

burg at Clinton, New Jersey, is a remnant of such. The incomplete nonmarine record may be due to the cycle having been cut short by the Taconic Disturbance or to post-Taconic erosion having removed the final stages of Martinsburg deposition before later beds were formed.

TACONIC DISTURBANCE

The Taconic Disturbance has only in the last few decades received more than passing recognition in Pennsylvania. In 1926 B. L. Miller (1926) called attention to evidence for it in the eastern counties. More recently, Cleaves and Willard (1939) reviewed the situation. They believe that the Taconic Disturbance affected Pennsylvania west to the Susquehanna Valley. At Susquehanna Gap Martinsburg shale and Bald Eagle conglomerate are in disconformity. The conditions there, when contrasted with those south of the gap where the Fairview or equivalent sandstone is preserved, imply folding followed by erosion of the Martinsburg. This area should be near the western limit of disturbance, since the Fairview and higher beds to the west are all conformable. East from the Susquehanna, angular unconformity separates the Martinsburg from the next higher beds, be these Bald Eagle or Shawangunk (Tuscarora). Therefore, the tectonic break is beneath the Bald Eagle—that is, pre-Richmond. The youngest beds affected by the folding are the Shochary sandstone of Pulaski age.

In New York the Taconic Disturbance is said to mark the close of the Ordovician. In Pennsylvania what has been called Taconic, it appears, happened before the close of the period, if the Bald Eagle and Juniata are Ordovician. Either the disturbance in Pennsylvania is not precisely synchronous with that in New York or the Pennsylvania sequence allows more precise dating.

In eastern Pennsylvania the deposition of Martinsburg sandstones of Pulaski age was followed by the so-called Taconic Disturbance. Erosion then beveled the folded Martinsburg. The deposits of the Bald Eagle and subsequent Silurian beds spread across the eroded edges of the Martinsburg shales and sandstones and mark the resumption of sedimentation.

Mention of the Bald Eagle and Juniata as formed after the Taconic Disturbance is anticlimactic, yet their Ordovician age is recognized. They follow a disturbance which succeeded the Martinsburg. If they are truly Ordovician, we must acknowledge either that a system may include units which are not members of its major sedimentation cycle or that the Taconic movement was intra- not interperiodic in Pennsylvania.

SUMMARY

(1) The Ordovician clastic sediments in Pennsylvania consist of the Martinsburg group, the Reedsville shale, the Bald Eagle sandstone and conglomerate, and the Juniata red beds.

(2) The ages and interrelations of the Ordovician clastic sediments in Pennsylvania may be summarized as follows:

Age		Central Pennsylvania	South-central Pennsylvania	Eastern Pennsylvania
SILURIAN		Tuscarora	Tuscarora	Shawangunk
ORDOVICIAN	Richmond	Juniata	Juniata	DISCONFORMITY
		Bald Eagle	Bald Eagle	Bald Eagle UNCONFORMITY
	Maysville	Reedsville: Sandy upper	Martinsburg: Fairview sandstone	Martinsburg: Shochary sandstone
	Eden	Reedsville: Shaly lower	Martinsburg: Shaly lower or Dauphin beds	Martinsburg: Shale and slate; Jonestown
		Coburn		Jacksonburg
	Trenton		Chambersburg	

(3) By structures, stratigraphy, paleontology, and field relations the marine portion of the Martinsburg group resolves into two principal parts, the upper sandstones and the lower shales or slates, not three parts as sometimes stated.

REFERENCES CITED

The following list is not intended to be a complete bibliography of the Ordovician clastic units in Pennsylvania but includes the references cited together with a few others used but not directly mentioned.

Bassler, R. S. (1919) *Report on the Cambrian and Ordovician formations of Maryland*, Md. Geol. Survey.

Bayley, W. S., Salisbury, R. D., and Kümmel, H. B. (1914) *Raritan folio [New Jersey]*, U. S. Geol. Survey, Atlas 191.

Behre, C. H., Jr. (1924) *Structures of the slates of northeastern Pennsylvania* (Abstract), Geol. Soc. Am., Bull., vol. 35, p. 100-101.

Behre, C. H., Jr. (1925) *Taconic folding in the Martinsburg shales* (Abstract), Geol. Soc. Am., vol. 36, p. 157-158.

—— (1926) *Observations on structures in the slates of Northampton County, Pennsylvania,* Jour. Geol., vol. 34, p. 481-506.

—— (1927) *Slate in Northampton County, Pennsylvania,* Pa. Topog. Geol. Survey, 4th ser., Bull. M 9.

—— (1928) *Geologic factors in the development of the eastern Pennsylvania Slate Belt,* Am. Inst. Min. Metall. Eng., Tech. Pub. 66, p. 1-18.

—— (1933) *Slate in Pennsylvania,* Pa. Topog. Geol. Survey, Bull. M 16.

Butts, Charles, Swartz, F. M., and Willard, Bradford (1939) *Tyrone quadrangle,* Pa. Topog. Geol. Survey, 4th ser., Atlas 96.

——, and Moore, E. S. (1936) *Geology and mineral resources of the Bellefonte quadrangle, Pennsylvania,* U. S. Geol. Survey, Bull. 855.

Claypole, E. W. (1885) *A preliminary report on the palaeontology of Perry County,* Pa. 2d Geol. Survey, vol. F 2.

Dale, T. N. (1906) *Slate deposits and slate industry of the United States,* U. S. Geol. Survey, Bull. 275.

D'Invilliers, E. V. (1891) *Report on the geology of the four counties, Union, Snyder, Mifflin and Juniata,* Pa. 2d Geol. Survey, vol. F 3.

—— (1884) *The geology of Centre County,* Pa. 2d Geol. Survey, vol. T 4.

Goldring, Winifred (1931) *Handbook of paleontology for beginners and amateurs,* N. Y. State Mus., Handbook 10.

Gordon, S. G. (1921) *Ordovician basalts and quartz diabases in Lebanon County, Pennsylvania,* Acad. Nat. Sci. Philadelphia, Pr., vol. 72, p. 354-357.

Hintze, F. F. (1918) *Age of the Martinsburg shale as interpreted from its structural and stratigraphical relations in eastern Pennsylvania* (Abstract), Geol. Soc. Am., Bull., vol. 29, p. 94-95.

Kay, G. M. (1937) *Stratigraphy of the Trenton group,* Geol. Soc. Am., Bull., vol. 48, p. 233-302.

Kümmel, H. B., and Weller, Stuart (1902) *The rocks of the Green Pond Mountain region,* N. J. Geol. Survey, Ann. Rept. 1901, p. 1-51.

Lesley, J. P. (1892) *Summary description of the geology of Pennsylvania,* Pa. 2d Geol. Survey, vol. I, p. 525-711.

Lewis, J. V., and Kümmel, H. B. (1915) *The geology of New Jersey,* N. J. Geol. Survey, Bull. 14. (Revised edition issued as Bull. 50, 1940.)

Miller, B. L. (1925) *Allentown quadrangle,* Pa. Topog. Geol. Survey, Atlas 206.

——, (1926) *Taconic folding in Pennsylvania,* Geol. Soc. Am., Bull., vol. 37, p. 497-512.

——, Fraser, D. M., Miller, R. L., *et al.* (1939) *Northampton County, Pennsylvania,* Pa. Topog. Geol. Survey, Bull. C 48.

——, ——, Willard, Bradford, and Wherry, E. T. (1941) *Lehigh County, Pennsylvania,* Pa. Topog. Geol. Survey, Bull. C 39.

Miller, R. L. (1937a) *Martinsburg limestones in eastern Pennsylvania,* Geol. Soc. Am., Bull., vol. 48, p. 93-112.

—— (1937b) *Stratigraphy of the Jacksonburg limestone,* Geol. Soc. Am., Bull., vol. 48, p. 1687-1718.

Moseley, J. R. (1938) *Notes on the structure and stratigraphy of the Martinsburg formation,* Ms. on file with Pa. Topog. Geol. Survey.

Peck, F. B. (1904) *Basal conglomerate in Lehigh and Northampton Counties, Pennsylvania* (Abstract), Geol. Soc. Am., Bull., vol. 14, p. 518-521.

Peck, F. B. (1908) *Geology of the cement belt, in Lehigh and Northampton counties, Pensylvania,* Econ. Geol., vol. 3, p. 37-76.

Platt, Franklin (1881) *The geology of Blair County,* Pa. 2d Geol. Survey, vol. T.

Rogers, H. D. (1836) *First annual report of the State Geologist [of Pennsylvania],* Harrisburg.

——— (1838) *Second annual report of the geological exploration of the State of Pennsylvania,* Harrisburg.

——— (1858) *Geology of Pennsylvania,* [First] Pa. Geol. Survey.

Sanders, R. N. (1883) *Slate belt and quarries,* in *The geology of Lehigh and Northampton counties,* Pa. 2d Geol. Survey, Rept. Prog. D 3, vol. 1, p. 83-160.

Spencer, A. C., Kümmel, H. B., Wolff, F. E., Salisbury, R. D., and Palache, Charles (1908) *Franklin Furnace Folio [New Jersey],* U. S. Geol. Survey, Atlas 161.

Stevenson, J. J. (1882) *The geology of Bedford and Fulton counties,* Pa. 2d Geol. Survey, vol. T 2.

Stose, G. W. (1910) *Mercersburg-Chambersburg Folio [Pennsylvania],* U. S. Geol. Survey, Atlas 170.

——— (1930) *Unconformity at the base of the Silurian in southwestern Pennsylvania,* Geol. Soc. Am., Bull., vol. 41, p. 629-658.

Stose, G. W., and Jonas, A. I. (1923) *Ordovician overlap in the Piedmont province of Pennsylvania and Maryland,* Geol. Soc. Am., Bull., vol. 34, p. 507-524.

——— (1927) *Ordovician shale and associated lava in southeastern Pennsylvania,* Geol. Soc. Am., Bull., vol. 38, p. 505-536.

——— (1933) *Geology and mineral resources of the Middletown quadrangle, Pennsylvania,* U. S. Geol. Survey, Bull. 840.

Swartz, C. K., and Swartz, F. M. (1931) *Early Silurian formations of southeastern Pennsylvania,* Geol. Soc. Am., Bull., vol. 42, p. 621-662.

Ulrich, E. O. (1911) *Revision of the Paleozoic systems,* Geol. Soc. Am., Bull., vol. 22, p. 281-680.

——— (1926) *Relative values of criteria used in drawing the Ordovician-Silurian boundary,* Geol. Soc. Am., Bull., vol. 37, p. 279-348.

Urry, W. D. (1936) *Post-Keweenawan time scale, Nat. Res. Council,* Rept., Comm. on Measurement Geol. Time, p. 35-40.

Ward, Freeman (1932) *The Martinsburg shale along the Delaware River,* Ms. on file with Pa. Topog. Geol. Survey.

——— (1934) *The Martinsburg Shale, report number 2,* Ms. on file with Pa. Topog. Geol. Survey.

——— (1936) *The Martinsburg shale as seen in the Eckville-Lynnport-Kempton area, Pennsylvania,* Ms. on file with Pa. Topog. Geol. Survey.

——— (1937) *The Martinsburg of the Shochary region,* Ms. on file with Pa. Topog. Geol. Survey.

——— (1939) *Martinsburg shale, Shartlesville-Straustown,* Ms. on file with Pa. Topog. Geol. Survey.

Weller, Stuart (1903) *Report on paleontology, vol. III, The Paleozoic faunas,* N. J. Geol. Survey.

Wherry, E. T. (1909) *The early Paleozoic of the Lehigh Valley district, Pennsylvania,* Science, n. ser., vol. 30, p. 416.

White, I. C. (1885) *The geology of Huntingdon County,* Pa. 2d Survey, vol. T 3.

Willard, Bradford (1939) *Ordovician shales of southeastern Pennsylvania,* Pa. Acad. Sci., Pr., vol. 13, p. 126-133.

Willard, Bradford (1940) *Recurrent Paleozoic continental facies in Pennsylvania,* N. Y. Acad. Sci., Annals, vol. 40, art. 4, p. 267-288.

—— (1941) *The Harrisburg axis,* Pa. Acad. Sci., Pr., vol. 15, p. 97-102.

Willard, Bradford, and Cleaves, A. B. (1938) *A Paleozoic section in south-central Pennsylvania,* Pa. Topog, Geol. Survey, Bull. G 8.

—— — —— (1939) *Ordovician-Silurian relations in Pennsylvania,* Geol. Soc. Am., Bull., vol. 50, p. 1165-1198.

Wilmarth, M. G. (1938) *Lexicon of geologic names of the United States,* U. S. Geol. Survey, Bull. 896.

Lehigh University, Bethlehem, Pennsylvania.

Manuscript received by the Secretary of the Society, May 3, 1943.
Published with permission of the State Geologist of Pennsylvania.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 54, PP. 1123-1168, 9 PLS., 6 FIGS. AUGUST 1, 1943

STRUCTURE OF CENTRAL PART OF SAWTOOTH RANGE, MONTANA

BY CHARLES DEISS

CONTENTS

Page

Abstract 1124
Introduction 1125
General statement 1125
Location of Sawtooth Range 1125
Summary of previous work in area 1127
Acknowledgments 1129
Rocks comprising central part of Sawtooth Range 1129
General statement 1129
Cambrian formations 1132
General considerations 1132
Pagoda limestone 1132
Steamboat limestone 1132
Switchback shale 1133
Devils Glen dolomite 1133
Devonian rocks 1134
Mississippian rocks 1135
Hannan limestone 1135
Jurassic rocks 1136
General statement 1136
Rierdon Gulch section 1136
Ellis formation 1139
Cretaceous formations 1140
General statement 1140
Rierdon Gulch section 1140
Kootenai formation 1143
Colorado shale 1144
Igneous rocks 1145
Pleistocene deposits 1145
Recent deposits 1147
Structural provinces in central part of Sawtooth Range 1147
Eastern structural province 1149
Structure along mountain front 1149
General conditions 1149
Teton anticline 1149
Structure near Ear Mountain 1150
Structure west of mountain front 1150
General statement 1150
Structure south of Deep Creek 1150
Structure north of Deep Creek 1151

Page

Central structural province 1151
General statement 1151
Imbrication near Rocky Mountain and Twin Peak 1153
Folds in relation to high-angle thrusts 1153
General considerations 1153
Structure east of Teton Peak 1154
Western structural province 1154
Location 1154
Structure south of Circle Creek 1154
Folds and thrusts north of Cabin Creek 1155
General considerations 1155
Beartop anticline 1157
Grouse Creek syncline 1158
Folded low-angle overthrusts 1158
Structures above the low-angle overthrusts 1159
Summary of geologic structure in central part of Sawtooth Range 1160
Pre-Pleistocene history of Sawtooth Range 1162
General considerations 1162
Late Tertiary uplift 1163
Quaternary history of Sawtooth Range 1163
Conclusions 1165
References cited 1165

ILLUSTRATIONS

Figure Page

1. Map showing location of area 1126
2. Index map of central part of Sawtooth Range 1128
3. Structure sections across eastern structural province 1148
4. Structure sections across central structural province 1152
5. Structure sections across western structural province 1156
6. Structure sections across central part of Sawtooth Range 1161

Plate Facing page

1. Twin Peak and crest of range 1136
2. Rierdon Gulch section of Ellis formation 1137
3. Kootenai formation 1144
4. Glacial drift on Kootenai formation, and front of Sawtooth Range 1145
5. Ear Mountain and ridges north of Cabin Creek 1150
6. North side of Deep Creek, and Slim Gulch 1151
7. Rocky Mountain and Teton Peak 1154
8. Ridges west of Big George Gulch and north of Grouse Creek 1155
9. Beartop anticline and post-Pleistocene canyon in Slim Gulch 1158

ABSTRACT

The Sawtooth Range is south of Glacier National Park and forms 85 miles of the Rocky Mountain front in northwestern Montana. The range averages 9 miles in width, consists of a broad northeastward-pointing arc, and extends north across the Saypo quadrangle.

The sedimentary rocks exposed in the Sawtooth Range are approximately 5500 feet thick, are Paleozoic and Mesozoic in age, and are divided into nine formations:

Pagoda and Steamboat (Middle Cambrian), Switchback (Middle and Upper Cambrian), and Devils Glen (Upper Cambrian), unnamed formation (Upper Devonian), Hannan (Mississippian), Ellis (Upper Jurassic), and Kootenai and Colorado (Lower and Upper Cretaceous).

Three structural provinces occur in the central part of the Range: an eastern province, characterized by westward-dipping high-angle to moderately low-angle thrusts that increase in number northward; a central province, characterized by closely spaced, westward-dipping, high-angle thrusts, and by drag-folding of the Devonian and Mississippian rocks comprising the imbricated slices; and a western province, characterized by folded, low-angle overthrusts, above which the rocks are compressed into large open folds.

The structures were produced by stresses from the west during the Laramide orogeny. The mountains were maturely eroded during the Tertiary, when the east-west courses of the main streams were established. Uplift in the Pliocene? raised the range to its present altitude but did not cause additional deformation.

INTRODUCTION

GENERAL STATEMENT

During the field seasons of 1940 and 1941, the writer mapped the geology in the central and western parts of the Saypo quadrangle, Montana, on the scale 1/62,500. All the field work in 1941 was done in the central part of the Sawtooth Range. The writer worked in the southern part of the range with C. H. Clapp in 1933 and completed mapping the areal geology of the part of the range between the Sun River and the south edge of the Saypo quadrangle (Fig. 2) in 1940. The field work has progressed to the point where some tentative conclusions may be published concerning the larger geologic structures in the central part of the Sawtooth Range.

The stratigraphy and structure of the southwestern part of the Saypo quadrangle (Deiss, 1943, p. 205-262) has already been discussed. The present report is a companion to that paper, and represents the second publication which has resulted from the writer's field work in the Saypo quadrangle for the Geological Survey, U. S. Department of the Interior.

LOCATION OF SAWTOOTH RANGE

The Sawtooth Range forms the front of the main body of the Rocky Mountains south of Glacier National Park in northwestern Montana. The range is broadly arcuate, the convex side of the arc being directed eastward. The range extends 85 miles from the North Fork of Dearborn River northward, N. 20° W., and finally N. 45° W. to the South Fork of Two Medicine Creek. The east edge of the range fronts on the plains (Fig. 1), above which the mountains rise 2000 to nearly 4000 feet. The east boundary of the mountains is an irregular series of generally high-angle thrusts along which massive limestones of the Hannan (Mississippian) and Devonian were pushed over Mesozoic shales and sandstones on the plains. When seen from the plains the broken limestone cliffs

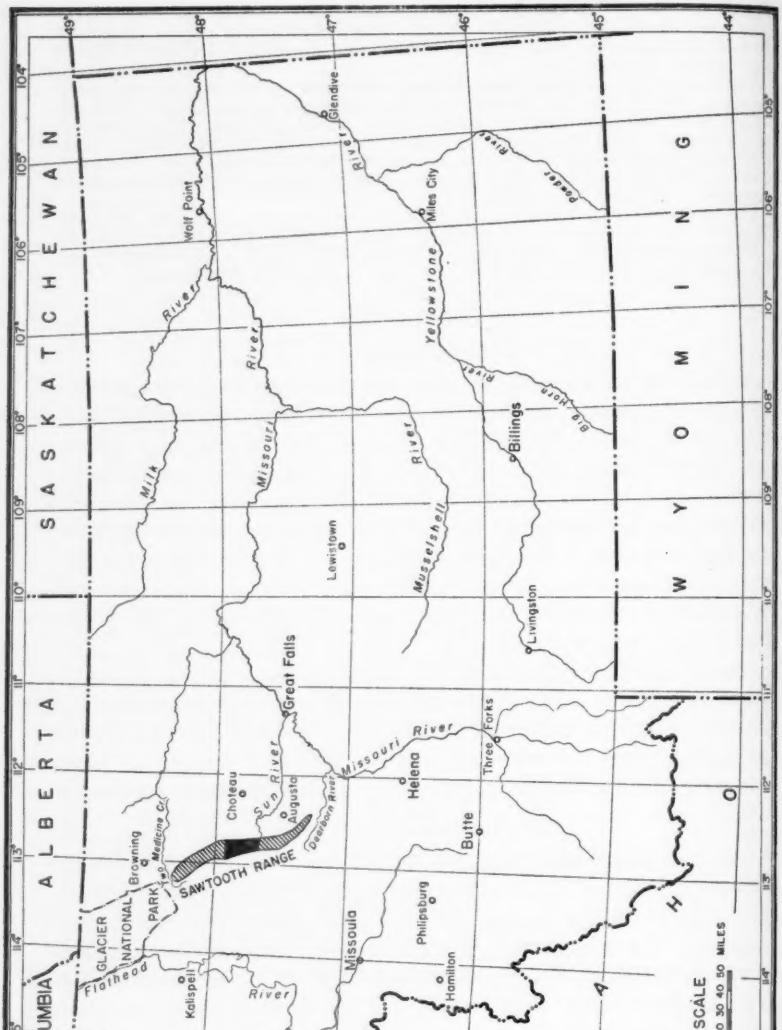


FIGURE 1.—*Map showing location of area*

above the thrust faults seem to rise in a sheer wall which forms an abrupt and imposing front for this part of the Rocky Mountains.

The Sawtooth Range is 2 to 13 miles in width and averages nearly 9 miles throughout most of its length. The widest part is north of Route Creek and the Middle Fork of Teton River (Fig. 2). In this area also the geologic structure is most complex. The Sawtooth Range is bounded on the west by the South and North Forks of Sun River, the South Fork of Trail Creek, Strawberry Creek, South Badger Creek, and the South Fork of Two Medicine Creek. The range is separated structurally from the Lewis and Clark Range on the west and from the Livingston Range on the north by the Lewis overthrust.

The Sawtooth Range occupies much of the Lewis and Clark National Forest, but the northwest part of the range is in the Flathead National Forest. The crest of the range, between the parallels 47°58′ and 48°8′, is part of the Continental Divide. The range lies between meridians 112°30′ and 113°15′ W. Long. and occupies parts of Flathead, Lewis and Clark, Pondera, and Teton counties, Montana. The part of the Sawtooth Range discussed in this paper is in the central part of the Saypo quadrangle, between the Sun River and Middle Fork of Teton River (Fig. 2).

The geographic names used in this paper are those used locally and are published on the official maps of the Lewis and Clark National Forest by the United States Forest Service. Many of the names of streams and mountain peaks are different from those given on the Saypo quadrangle which was surveyed in 1901 and published in 1903. (*Compare* Figure 2 and a copy of the Saypo quadrangle.)

FIGURE 1.—*Map showing location of area*

SUMMARY OF PREVIOUS WORK IN AREA

Apparently only 9 or 10 geologists ever worked in the central part of the Sawtooth Range, and the six papers that were published before 1942 dealt with isolated or generalized aspects of the geology of the region. In a recent paper (Deiss, 1943, p. 209-211), the results attained by nearly all the geologists who worked in the mountains of the Saypo quadrangle were summarized. Because the central part of the range is in the Saypo quadrangle the summary applies to the area being described and does not need to be repeated here. The only field work not discussed in the summary was done between 1901 and 1903 by Calhoun (1906, p. 15-17) who studied the glacial geology along the front of the mountains. Calhoun made reconnaissance traverses up the main streams across the central part of the Sawtooth Range.

The writer worked in the southern part of the mountains in 1933 and in 1940, but most of the field work which forms the basis of this report

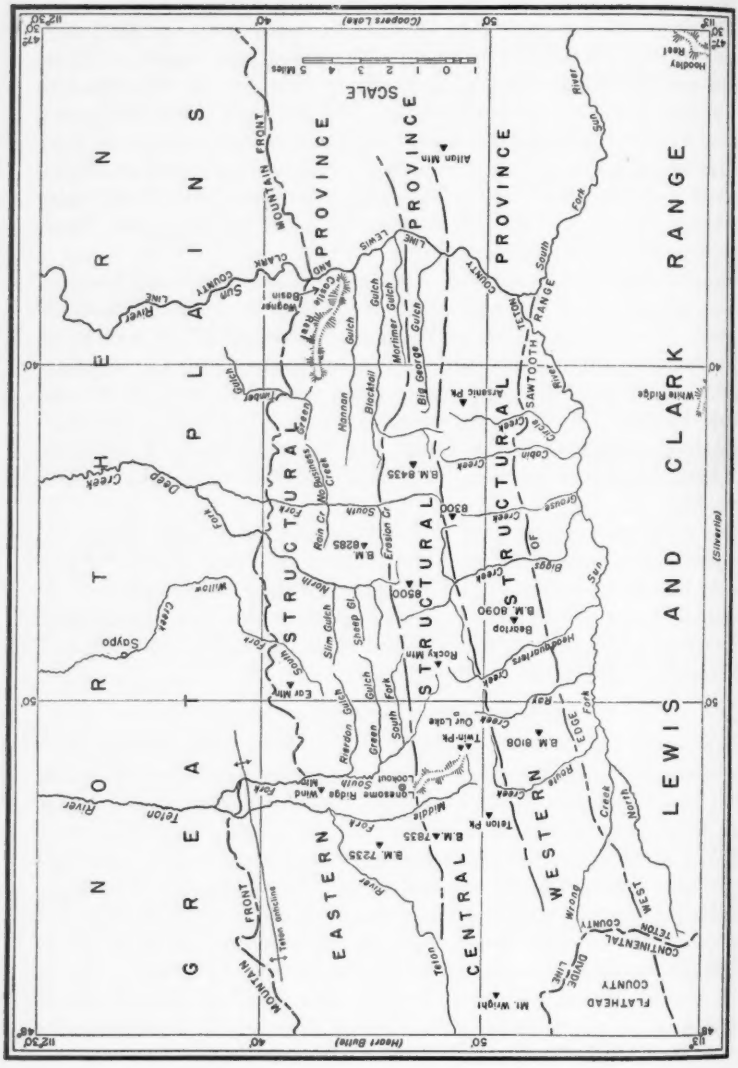


FIGURE 2.—*Index map of central part of Sawtooth Range*

was done between June and September 1941. A detailed account of the stratigraphy and structure of the Sawtooth Range never has been published, but the structure in the part of the range south of the area under consideration was discussed (Deiss, 1943, p. 248-253) recently.

ACKNOWLEDGMENTS

Doctor G. R. Mansfield discussed the geologic problems with the writer, criticized some of the structure sections, carefully read the manuscript, and made a number of helpful suggestions. Doctor Josiah Bridge worked with the writer in the Sawtooth Range in August 1941 and gave much help with the stratigraphic and structural problems. Doctor Bridge also read the manuscript. Doctor J. B. Reeside, Jr., identified the Jurassic fossils, and Doctor C. S. Ross identified the minerals contained in the rock specimens collected from the Sawtooth Range. The writer gratefully acknowledges the help given by each of these men. David J. Varnes was the field assistant during the field work in the central part of the Sawtooth Range, and for his helpful suggestions and sustained energy in the field the writer extends his appreciation and thanks. Montana State University provided the field equipment and transported all the food and supplies to the mountains during the field work. The University also provided laboratory space, equipment, supplies, and clerical assistance for preparation of field data and of the finished manuscript. In addition, the writer was freed from some routine teaching duties. For this assistance the writer gratefully acknowledges his indebtedness.

Figure 2.—*Index map of central part of Sawtooth Range*

ROCKS COMPRISING CENTRAL PART OF SAWTOOTH RANGE

GENERAL STATEMENT

The rocks exposed in the Sawtooth Range are of Middle and Upper Cambrian, Upper Devonian, Mississippian, Upper Jurassic, and Cretaceous ages. The youngest formation (Ahorn quartzite) of the Belt series in the Lewis and Clark Range underlies the basal Cambrian sandstone in the Sawtooth Range and appears in some of the structure sections. Although the Ahorn quartzite and Hoadley formation (Deiss, 1943, p. 216-218) are represented in the structure sections (Fig. 3, B-B′), Proterozoic rocks do not crop out in the central part of, and probably nowhere in, the Sawtooth Range.

The formations in the southern part of the Sawtooth Range recently were described in detail (Deiss, 1943, p. 211-240). The Paleozoic and Mesozoic formations in the southern part of the range also are present in the central part of the range and, therefore, need not be redescribed

TABLE 1.—*Formations exposed in central part of Sawtooth Range*

System	Series	Group and Formation	Character	Thickness in Feet
Quaternary	Recent	Alluvium	Muds, sands, and gravels generally restricted to larger valley floors. Silts caught in beaver ponds probably responsible for many valley flats formerly called "flood plains."	
	Pleistocene	Glacial drift	Recessional, lateral, medial and ground moraines deposited by Wisconsin alpine glaciers. Fluvioglacial sands and gravels in many valleys. Possibly some outwash mapped as Pleistocene is Recent alluvium.	1–250?
		Unconformity		
Cretaceous	Upper Cretaceous	Blackleaf sandy member of Colorado shale	Black, soft, smooth, extremely fissile shale interbedded with 2- to 24-foot units of gray-green calcareous sandstone in lower and upper parts. Near middle part of member is 42-foot unit of tan-green-gray massive fine- and medium-grained sandstone. Entire member not exposed.	205 exposed
	Lower Cretaceous	Kootenai formation	Lower 55 feet black-gray, micaceous and arenaceous lumpy shale interbedded with tan and green-gray lenticular beds of sandstone. Upper 1055 feet 20- to 40-foot units of maroon and green-gray shale which alternate with thinner units of green-gray sandstone, which increases in amount upward. Units of dove-gray limestone present in some localities. Near upper-middle part conglomerate composed of ¼ - to 7-inch pebbles of chert, monzonite, quartz, quartzite, and jasper in a matrix of medium-grained quartzitic sandstone.	1100–1500?
Jurassic	Upper Jurassic	Ellis formation	Lower few feet dull-gray, fine-grained massive quartzite overlain by 135 feet of black-gray and tan-gray shale interbedded with thin units of fossiliferous limestone. Medial 50 feet bright tan-buff arenaceous limestone and fine-grained sandstone. Upper 200 feet alternate 4- to 8-foot units of gray and buff calcareous shale interbedded with thin units of blue-gray limestone. Marine fossils of Divesian and Argovian age abundant at seven horizons.	250–390

		— Unconformity —		
Carboniferous	Mississippian	Hannan limestone	Basal limestone breccia overlain by 400 feet of black and tan brittle limestone. Medial 600 to 700 feet light-gray fossiliferous cherty crystalline limestone. Upper 300 feet buff and light-gray dense thin- and thick-bedded, finely crystalline dolomite which weathers white-gray.	1400–1500?
Devonian	Upper Devonian	Two new unnamed formations	Dolomite limestone and shale overlain by tan-gray finely to medium-crystalline fossiliferous limestone. Alternate units of drab-brown, petroliferous, arenaceous, thick-bedded dolomite and light-gray, hard, finely crystalline, thick- and thin-bedded limestone. All more or less petroliferous and argillaceous.	1000
		— Unconformity —		
Cambrian	Upper Cambrian	Devils Glen dolomite	White-gray to pale-buff-gray, finely crystalline, thick- and some thin-bedded dolomite. Mottled salmon-pink and coarser-grained in upper part of formation. Weathers white-gray and forms sheer cliffs.	200–250
	——— ?	Switchback shale	Green and gray soft shale, locally calcareous and arenaceous, interbedded with flaggy bedded magnesian limestone which weathers rusty tan. Contains youngest known Middle Cambrian trilobites, and others which belong to basal Upper Cambrian (*Cedaria*) fauna.	125–175?
	Middle Cambrian	Steamboat limestone	Pale-gray and tan fine-grained thick- and thin-bedded limestone overlain by interbedded tan-gray irregularly bedded fossiliferous limestone and green fissile shale. Shale in units 2 to 8 feet thick separated by much thicker units of limestone. Base of formation not exposed in central part of Sawtooth Range.	275
		Pagoda limestone	Green fissile shale interbedded with thin-bedded limestone, overlain by cream- and chocolate-gray finely crystalline limestone, thin-bedded in lower and upper parts, and oolitic and thick-bedded in middle part.	Thickness exposed unknown

here. The lithologic characteristics of some of the formations, however, change laterally, and the Cambrian rocks below the Pagoda limestone are not exposed in the area being discussed.

CAMBRIAN FORMATIONS

General considerations.—Only four of the nine Cambrian formations recognized in the Lewis and Clark Range (Deiss, 1939a, p. 34-47) 8 miles to the west are exposed in the central part of the Sawtooth Range. These formations, from oldest to youngest, are: (1) the upper part of the Pagoda limestone, (2) the Steamboat limestone (Middle Cambrian), the lower half of which was not found in most of the map area, (3) the Switchback shale (Middle and Upper Cambrian), which seems to be somewhat thicker than it is farther west and south, and (4) the Devils Glen dolomite (Upper Cambrian), which averages 200 feet or more in thickness. The Pentagon shale, 290 feet thick, rests on the Pagoda limestone at Pentagon Mountain (Deiss, 1939a, p. 15) in the Lewis and Clark Range but has not been found in the central part of the Sawtooth Range.

Pagoda limestone.—The Pagoda limestone crops out only in one locality in the map area and is not completely exposed. The upper part of the formation is exposed on the west side of Big George Gulch where the beds are folded and sheared. At Big George Gulch the Pagoda consists of more green shale and less massive limestone than at its type locality on Prairie Reef (Deiss, 1939a, p. 40-41) 11 miles southwest of Big George Gulch in the Silvertip quadrangle. Further, the rocks are so intensely folded and mashed on the west side of Big George Gulch that the Pagoda cannot be separated readily from the overlying Steamboat limestone.

Steamboat limestone.—The Steamboat limestone is exposed only on the west side of the range, except for small outcrops north and south of the Middle Fork of Teton River, south of Teton Peak (Pl. 7, fig. 2), and northeast of Twin Peak. Nowhere in the central part of the Sawtooth Range is the Steamboat limestone completely exposed except possibly on the west side of Big George Gulch. The largest outcrops are in Cabin Creek (Pl. 5, fig. 2) and on the ridge north of Biggs Creek. At the latter locality, the gray, irregularly bedded limestone contains many flakes and nodules of tan clay and several poorly exposed thin units of green shale. The limonite in the limestone and the tan clay flakes cause the Steamboat to weather to a characteristic bright buff tan color wherever the formation crops out. Thin lenticular limestone intercalated in the green shales contain disarticulated trilobites of the young Middle Cambrian *Thomsonaspis* fauna (Deiss, 1939a, p. 45; 1939b, p. 1005; 1940, p. 785).

Switchback shale.—The Switchback shale is exposed at many more localities than is the Steamboat limestone but, like the Steamboat, is confined to the western part of the Sawtooth Range. The only two occurrences of the Switchback east of the crest of the range are on the northeast spur of Teton Peak and on the ridge a mile west of Lonesome Ridge Lookout. In the central part of the range the Switchback consists of 150 feet or more of black-green, dark-gray, and dark-maroon, fissile to chunky, finely micaceous and arenaceous shale. At irregularly separated horizons are intercalated beds of gray-brown-weathering, thick-bedded limestone; crystalline, thin-bedded, fossiliferous limestone that contains many grains of limonite which causes the rock to weather bright rusty tan; and thick beds (6 to 16 inches) of intraformational conglomerates whose matrix is medium to coarsely crystalline and whose pebbles are well rounded, finely crystalline limestone. Glauconite occurs in the matrix of some of the conglomerates. The upper part of the Switchback consists of alternating units of green and gray shale, and pale buff-weathering, argillaceous, soft, thin-bedded limestone.

Norman Denson is studying the youngest Middle Cambrian trilobites from the Switchback shale in the Dearborn River (Coopers Lake quadrangle). Denson (Deiss, 1943, p. 223) was the first to discover trilobites of both late Middle Cambrian and early Waucoban age in the middle and upper parts of the Switchback shale. G. O. Raasch recently examined the fossils of the younger fauna in the Switchback shale collected by Denson in the Dearborn Canyon. Raasch (personal communication) identified the following species and commented upon their age as follows: "The fauna is certainly Dresbach and presumably of the *Crepicephalus* Zone."

Fossils:

Coosella sp.
Kingstonia? sp.
Terranovella? sp.
Weeksina sp.

The Upper-Middle Cambrian boundary, therefore, is somewhere in the middle or upper part of the Switchback shale in northwestern Montana.

Devils Glen dolomite.—The Devils Glen (Upper Cambrian) dolomite consists of light-gray, finely crystalline, massive, thick-bedded dolomite which is mottled pink and buff in some beds and locally contains small amounts of quartz sand.

The Devils Glen dolomite in the central part of the Sawtooth Range has the same composition and appearance as that in the southern part of the range on Allan Mountain (Deiss, 1943, p. 223-224). North and south of Biggs Creek, however, spherulites resembling large oölites are numerous

throughout 30 to 40 feet of thickness in the upper beds of the Devils Glen dolomite. C. S. Ross studied rock specimens petrographically and comments on the structure as follows (personal communication): "Microscopic examination shows a coarsely crystalline limestone with the oölite-like grains differing from the rest of the rock only in color." Locally, the spherulites are concentrated in lenses or stringers which alternate with fucoidal? limestones. The Devils Glen dolomite weathers white gray (Pl. 5, fig. 2) and usually forms cliffs in the central part of the range as it does nearly everywhere it crops out in the mountains of northwestern Montana.

DEVONIAN ROCKS

The Devonian rocks are approximately 1000 feet thick in the central part of the Sawtooth Range, are Upper Devonian in age, and are similar in composition and thickness to those in the southern part of the range described from Allan Mountain (Deiss, 1943, p. 226-227). However, the Devonian rocks in the northern part of the area differ slightly from those in the south in several ways. Red and green shale correlated with the previously described Glenn Creek shale member (Deiss, 1933, p. 42), which occurs above the basal limestone of the Devonian in the Lewis and Clark Range on White Ridge (Fig. 2), is absent in the Allan Mountain section (Deiss, 1943, p. 226-227). The Glenn Creek member, however, is represented by pale-green and buff shale and argillaceous limestone, 15 to 25 feet thick, throughout the central part of the Sawtooth Range. The unit is an excellent marker bed on top of the white Devils Glen dolomite. In this part of the range the shale of this unit acted as a lubricant along the thrust faults. Buff and gray limestone which could be correlated with the previously described White Ridge limestone member of the Lewis and Clark Range (Deiss, 1933, p. 43) is absent. Possibly the buff, argillaceous limestones at the base of the shale in the central part of the Sawtooth Range are equivalent to the beds on Allan Mountain that have been correlated with the White Ridge member.

The rocks equivalent to the Coopers Lake limestone in the Lewis and Clark Range (Deiss, 1933, p. 43; 1943, p. 227) are thinner in the Sawtooth Range. This unit thickens northward from Allan Mountain and contains fewer fossils but so many flakes, blebs, and stringers of buff and gray siliceous clay that the rock lithologically resembles the Steamboat limestone (Cambrian).

In most of the central part of the range the beds correlated with the Lone Butte member in the Lewis and Clark Range (Deiss, 1933, p. 43-44) are similar in composition to those in the same unit on Allan Mountain (Deiss, 1943, p. 226-227), but between Circle and Headquarters creeks

(Fig. 2) the upper 350 feet consists of more gray-weathering limestone and less buff shale.

The Devonian rocks in the central part of the range are being mapped as one or, locally, two formations which will be named when the report on the Saypo quadrangle is published.

MISSISSIPPIAN ROCKS

Hannan limestone.—The Hannan limestone (Deiss, 1943, p. 228-231) forms the highest peaks (Pl. 1, fig. 1) and many of the high ridges in the Sawtooth Range where it rests conformably on the Devonian.

The formation, 1400 feet thick, consists of a basal limestone breccia 4 to 25 feet thick overlain, in the northern part of the map area, by 400 feet of black and tan, brittle, finely crystalline, hard limestone. The next 600 to 700 feet is light-gray, crystalline, thick- and thin-bedded, fossiliferous, cherty limestone which weathers light-buff-gray. The upper 300 feet of the Hannan is dense, buff and pale-gray, finely crystalline, thick- and thin-bedded dolomite which weathers white gray (Pl. 1, fig. 2) and is correlated with the upper Mississippian Brazer limestone of Idaho.

The Hannan limestone in the central part of the Sawtooth Range differs in one important and in several minor lithologic features from that to the west and south in the Lewis and Clark Range and in the southern part of the Sawtooth Range. Throughout the mountains, south and west of the central part of the Sawtooth Range, the rocks above the basal limestone breccia are dark-tan-gray, finely crystalline, thin-bedded, usually fossiliferous limestones which contain much black- or dull-gray chert, and weather dull gray. This unit of the Hannan has been named the Dean Lake chert member in the Lewis and Clark Range (Deiss, 1933, p. 46). In the Sawtooth Range north of Deep Creek the beds that occupy the same stratigraphic position as the Dean Lake chert member consist of a basal unit 30 to 40 feet thick of black-gray brecciated, finely crystalline limestone which forms rounded cliffs. Above the breccia is 10 to 15 feet of blue-gray, thick-bedded, fossiliferous limestone (weathered zaphrentids and crinoids), in turn overlain by 15 to 20 feet of chocolate-maroon and black-gray, platy, calcareous shale which weathers to brown soil. The upper 325 to 375 feet of the unit consists of black-gray, hard, brittle, finely crystalline, thick- and thin-bedded unfossiliferous limestone which weathers lighter gray than the fresh fracture. Many beds weather drab buff or pale tan and to irregular, raised, finely wavy bands 0.2 to 200 mm. thick. Some of the limestone which forms the bands is the same color on fresh fracture as the other part of the beds, whereas the unweathered limestone which forms other bands is steel tan gray on fresh

fractures. Irregularly distributed throughout this unit are a few 2- to 4-foot black calcareous platy shales, and shaly limestones. The limestone in the upper part of the unit is faint tan gray, more coarsely crystalline, thicker- and more massive-bedded, and weathers lighter gray. In contrast with the typical Dean Lake member, chert is rare or absent in these limestones; fossils are scarce and poorly preserved; and the rocks weather buff tan so that, from a distance, they look like those of the Devonian. This unit was not mapped separately but is important in deciphering the geologic structure of the central part of the Sawtooth Range. In describing the geologic structures the unit is referred to, for convenience, as the black and tan unit.

The black and tan unit of the Hannan is overlain by the typical light-gray-weathering, thick-bedded, fossiliferous, cherty limestones equivalent to the Rooney chert member described in the Flathead and Lewis and Clark ranges (Deiss, 1933, p. 47; 1943, p. 229-230). The upper part of the Hannan, as in the southern part of the Saypo quadrangle (Deiss, 1943, p. 230), is composed of white-gray-weathering thick-bedded, finely crystalline, pale-buff and light-gray cherty dolomite (Pl. 1, fig. 2). The upper beds of this unit locally contain numerous quartz crystals one-sixteenth to one-half inch and occasionally as much as 1½ inches in length, segregated in geodal cavities. Poorly preserved large coralla of *Syringopora* sp., and *Lithostrotion*? sp. are present but rare in the upper beds.

JURASSIC ROCKS

General statement.—The rocks referred to the Ellis formation in the Sawtooth Range are Upper Jurassic (Divesian and Argovian) of the European classification, and are tentatively correlated with the upper part of the Ellis formation in the Little Rocky Mountains of central Montana (Deiss, 1943, p. 232). In the southern part of the Sawtooth Range the Ellis formation is almost 250 feet thick (Deiss, 1943, p. 233-235), nearly the same as the minimum thickness reported by Stebinger (1918, p. 135) for the formation in the plains east of the range. The Ellis formation thickens northward and is 390 feet at the head of Rierdon Gulch (Fig. 2), where the following complete section was measured in 1941.

Rierdon Gulch section.—The section was measured in the S½ sec. 23, T. 24 N., R. 9 W., on the divide between the heads of Rierdon and Slim gulches. The section begins at an altitude of approximately 7550 feet, nearly 275 feet north of the saddle at the east end of the divide. The section traverse extends west on and near the crest of the divide between the heads of Rierdon and Slim gulches (Pl. 2, fig. 1).

FIGURE 1. TWIN PEAK SHOWING CHARACTERISTIC RIDGES FORMED OF STEEPLY DIPPING FAULTED HANNAN LIMESTONE
Je = Ellis formation, Ch = Hannan limestone.

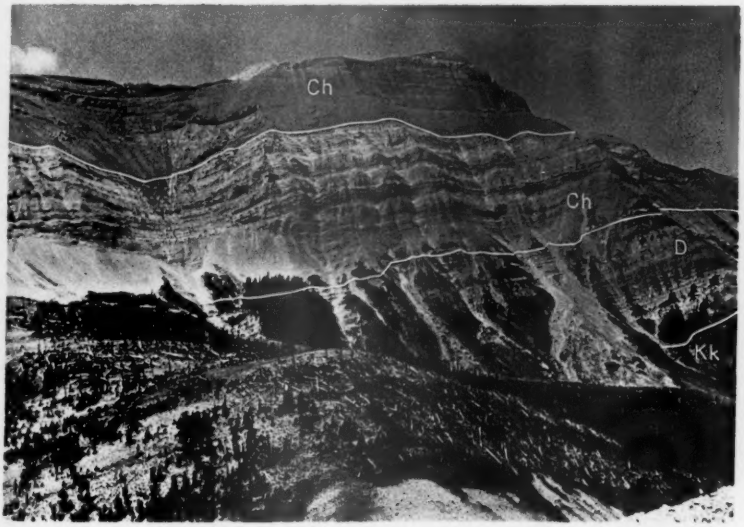


FIGURE 2. ENTIRE SECTION OF HANNAN LIMESTONE ON EAST SIDE OF CREST OF SAWTOOTH RANGE.
Kk = Kootenai formation, Je = Ellis formation, Ch = Hannan limestone, D = Devonian limestone (formation unnamed).

TWIN PEAK AND CREST OF RANGE

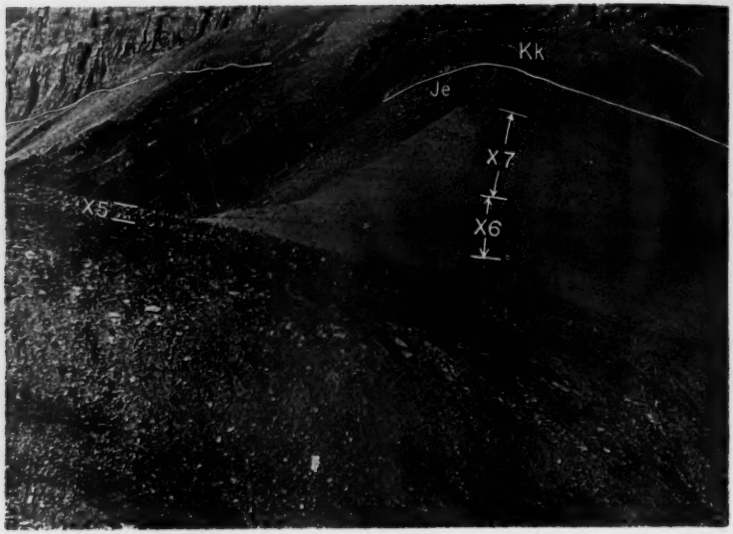


FIGURE 1. MIDDLE BRIGHT BUFF ARENACEOUS LIMESTONE AND UPPER BUFF AND GRAY SHALES OF ELLIS FORMATION

X5, X6, and X7 = Faunal zones of fossil locality 5. *See* Rierdon Gulch section.
Kk = Kootenai formation, Je = Ellis formation, Ch = Hannan limestone thrust upon Colorado shale.

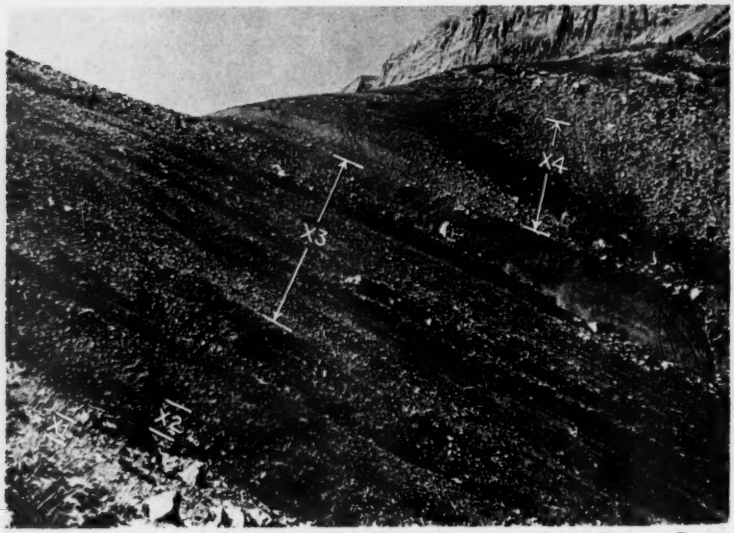


FIGURE 2. DARK SHALES AND INTERCALATED THIN BEDS OF LIMESTONE IN LOWER PART AND BRIGHT BUFF ARENACEOUS LIMESTONE IN MIDDLE PART OF ELLIS

X1, X2, X3, and X4 = Faunal zones of fossil locality 5. *See* Rierdon Gulch section.

RIERDON GULCH SECTION OF ELLIS FORMATION

	Feet	Meters
LOWER CRETACEOUS		
Kootenai formation		
Sandstone, shale, and some limestone: 1100 feet in thickness; marked at base by a tan-gray, fine-grained, hard sandstone. *See* Rierdon Gulch section of Kootenai formation on the following pages.		
UPPER JURASSIC		
Ellis formation		
15. Shale and limestone: dark- to blackish-gray, very slightly calcareous and micaceous shale, interbedded with finely arenaceous, argillaceous, finely crystalline limestone of which one bed 15 feet below top weathers bright tan. Unit weathers dark gray, and forms slope usually covered with talus of overlying shaly micaceous Kootenai sandstone	55	16.8
14. Shale and limestone: alternating units of dull-gray, fissile to chunky, calcareous shale; and many 2- to 6-inch beds of dull-gray and faint tan-gray, lithographic limestone; and blue-gray medium-crystalline, fossiliferous limestone which weathers tan buff. Top of fossil locality 5, zone 7	33	10.1
13. Shale and limestone: alternating 4- to 8-foot units of buff and gray, very calcareous shale which weathers pale gray and contains nodules of barite; and interbedded dull-gray argillaceous limestone which contains small pelecypods. Base of fossil locality 5, zone 7 (Pl. 2, fig. 1)	75	22.8
Fossils: *Camptonectes* cf. *C. extenuatus* Meek and Hayden; *Gryphaea nebrascensis* Meek and Hayden; *Pachyteuthis* sp.		
12. Shale and limestone: alternating zones of dark-gray fissile sale; pale-buff-gray and dull gray, extremely argillaceous, lithographic, fossiliferous limestone; and 2- to 6-foot zones of drab buff-gray chunky shale. Barite nodules average ¼ inch in diameter in drab-buff shales. Coarsely ribbed pelecypods, flat smooth brachiopods, and *Gryphaea* in upper shale. *Gryphaea* abundant in lower-middle part of unit. Unit weathers pale buff and gray. Fossil locality 5, zone 6 (Pl. 2, fig. 1)	38	11.6
Fossils: *Astarte packardi Meek*; *Camptonectes* sp.; *Grammatodon inornatus* Meek; *Gryphaea* aff. *G. impressimarginata* McLearn; *Pleuromya weberensis* Meek; *Trigonia montanensis* Meek		
11. Limestone: pale tan-gray and bright-buff, argillaceous, finely arenaceous, fossiliferous limetone in 1- to 6-inch beds. Weathers bright tan and forms ledge at top of tan-buff zone. Fossil locality 5, zone 5 (Pl. 2, fig. 1)	5–7	1.5–2.1
Fossils: *Astarte packardi* Meek; *Camptonectes bellistriatus* Meek; *C.* cf. *C. extenuatus* Meek and Hayden; *Eumicrotis curta* (Hall); *Ostrea* sp.; *Pachyteuthis* sp.; *Pentacrinus asteriscus* Meek and Hayden; *Protocardia* sp.		
10. Unit covered with soil of bright-buff-tan, calcareous, finely arenaceous mudstone or finely arenaceous, extremely argillaceous limestone. Fragments of *Pachyteuthis* species in lower beds	33	10.1
9. Limestone and sandstone: bright-buff-tan, fine-grained, very calcareous, fossiliferous, argillaceous sandstone which grades up into buff-gray finely arenaceous limestone. Weathers bright tan and forms small ledge in slope	1–1.5	0.3–0.5

	Feet	Meters
8. Limestone, shale and sandstone: buff-gray, extremely argillaceous and finely arenaceous, irregularly bedded, fossiliferous limestone which weathers bright buff tan, and contains many pelecypods; interbedded with some buff-gray shale which grades up into bright-tan, soft, calcareous, very thin-bedded sandstone. Unit more arenaceous up section. Fossil locality 5, zone 4, from base to middle of unit (Pl. 2, fig. 2)	25	7.6

Fossils:

Ammonite, juvenile, undetermined	*Ostrea strigilecula* White
Astarte meeki Stanton?	*Pholadomya kingi* (Meek)
Camptonectes bellistriatus Meek	*Pinna kingi* (Meek)
Eumicrotis curta (Hall)	*Pleuromya* sp.
Grammatodon? sp.	*P. weberensis* (Meek)
G. cf. *G. inornatus* Meek	*Protocardia sp., probably* new
Natica? sp.	*Trigonia montanensis* Meek

7. Shale and limestone: dull-gray, slightly fissile shale and intercalated gray limestone. Limestone weathers to nodular rounded pebbles on shale slope. Top of fossil locality 5, zone 3. Unit forms upper part of lower gray zone in Ellis	31	9.5
6. Shale and limestone: dull-gray shale and argillaceous shaly, fossiliferous, limestone in lower half, and drab-tan shale and pale buff-gray calcareous shale in upper half. Unit weathers gray and forms slope. Poorly preserved brachiopods and pelecypods in some of limestone beds	16	4.9
5. Shale and limestone: dark-gray, chunky and fissile, calcareous shale in 4- to 20-foot zones interbedded with 1- to 5-foot zones of gray, fine-grained, hackly, massive, thin-bedded, argillaceous, fossiliferous limestone and with other zones of rusty-brown arenaceous shale which contains grains of pyrite and limonite. Unit weathers dull gray streaked brown tan. Near top is 4-foot zone of drab-tan-weathering calcareous shale. Base of fossil locality 5, zone 3 in this unit	41	12.5

Fossils:

Dosinia aff. *D. jurassica* (Whitfield)	*Protocardia* sp., prob. new
Gryphaea sp.	*Tancredia inornata* Meek
Pleuromya weberensis Meek	*Volsella subimbricata* Meek
	V. sp., probably new

4. Limestone and shale: rusty-brown and drab-gray shale which contains much limonite and is interbedded with ½- to 3-inch beds of dull-gray, platy, fossiliferous, hard limestone, and some 2-inch medium crystalline gray limestone and 4- to 5-inch beds of pale-gray lithographic limestone which contains many tiny crystals of pyrite. Fossil locality 5, zone 2, in platy limestone 2 feet above base of unit	19	5.8

Fossil: *Tancredia inornata* Meek?

3. Limestone, shale and sandstone: dull-gray, arenaceous, finely banded limestone in ¼- to ¾-inch beds intercalated in black- to dull-gray, fissile shale. At top of unit is zone 4 to 5 inches thick of rusty tan-green-weathering thin-bedded limestone and calcareous sandstone. Beds and lenses of calcareous sandstone contain many pelecypods and brachiopods. Fossil locality 5, zone 1 (Pl. 2, fig. 2)	2.5	0.8

Fossils:

Astarte meeki Stanton	*Nucula* n. sp.
A. packardi White	*Ostrea* sp.
Cerithium sp., probably new	*Pachyteuthis* sp.
Dentalium sp.	*Tancredia inornata* Meek
Eumicrotis curta (Hall)	*Trigonia montanensis* Meek

	Feet	Meters
2. Shale, sandstone, and limestone: black, very finely arenaceous, fissile shale; contains minute crystals of gypsum, and is stained buff brown on bedding surfaces. Tan, finely banded, soft sandstone interbedded in lower part and one 5- to 6-inch bed of dull-gray argillaceous, more or less lithographic limestone in upper part of unit. Limestone contains ½- to 1-inch mud cracks on upper surface. Some 1- to 2-inch limonite concretions in upper shale	10	3.0
1. Quartzite: dull-gray, fine-grained, fairly homogeneous, thick-bedded, massive, locally finely banded; contains much limonite. Upper surface strongly rippled, and also rolled in waves 10 feet wide and as much as 2 feet high. Upper surface stained deep rusty brown and shows liesegang rings of limonite and hematite. Contact of quartzite on Hannan is irregular, but apparently conformable	1.5–3	0.5–0.9
Total thickness of Ellis formation	390	119.0

MISSISSIPPIAN

Hannan limestone

Dolomite: pale-tan-gray, and dull-gray, finely crystalling (nearly lithographic) thick-bedded, cherty, siliceous, fossiliferous; contains dark-gray chert in stringers and nodules. In geodes in chert are quartz crystals as much as 1 inch in length. Many weathered siliceous corals and fenestellids. Dolomite weathers white gray and breaks to angular fragments.

Ellis formation.—The basal 1 to 3 feet of the Ellis formation consists of dull-gray, fine-grained, massive quartzite which weathers rusty tan and rests on the irregular wavy upper surface of the upper Hannan limestone. The overlying 135 feet of the Ellis is black-gray and dull buff-gray shale interbedded with gray platy to massive, fossiliferous, argillaceous, and occasionally arenaceous limestone. The rocks in this unit weather gray and buff gray and form characteristic shale slopes of the lower Ellis (Pl. 2, fig. 2) wherever the formation is exposed in the central part of the range.

The medial 50 feet of the Ellis formation consists of bright tan-buff-weathering shaly and thick-bedded finely arenaceous fossiliferous limestone and calcareous fine-grained sandstone.

The upper 199 feet of the Ellis formation consists of alternating 4- to 8-foot units of dull-gray and buff calcareous shale and interbedded pale-blue-gray argillaceous fossiliferous limestone. This unit weathers dull buff gray and forms slopes characteristic of the upper part of the formation (Pl. 2, fig. 1) throughout the central part of the Sawtooth Range. The following species collected by Josiah Bridge in 1941 from the west end of Lonesome Ridge (Locality 6) were identified by J. B. Reeside, Jr. (personal communication), who says: "Same fauna as that collected at the head of Lange Creek in 1940 (Deiss, 1943, p. 232), probably not older than upper Ellis."

Fossils:

Camptonectes cf. *C. bellistriatus* Meek
Cardinia sp.
Gryphaea cf. *G. impressimarginata* McLearn
G. nebrascensis Meek and Hayden
G. cf. *G. planoconvexa* Whitfield
Ostrea sp.
Pachyteuthis densus (Meek and Hayden)
Pleuromya weberensis (Meek)
Quenstedticeras (Eboraciceras) aff. *Q. tumidum* Reeside
Macrocephalitid ammonites, several species, probably new
Serpula sp., probably unnamed

CRETACEOUS FORMATIONS

General statement.—The youngest indurated rocks in the central part of the Sawtooth Range are Cretaceous in age. The Lower Cretaceous is represented by continental sediments which comprise the Kootenai formation, and the Upper Cretaceous is represented by the lower part of the marine Colorado shale, the Blackleaf sandy member (Stebinger, 1918, p. 158-161). Diorite, intruded into the Cretaceous shales and sandstones along part of the west side of the range, forms a sill nearly 350 feet thick on Circle Creek. The sill thins northward and disappears between Headquarters and Ray creeks (Fig. 2). The intrusion probably occurred late in the Cretaceous (Deiss, 1943, p. 248).

Rierdon Gulch section.—The following section of Colorado and Kootenai rocks was measured just west of and on the same ridge as the Ellis formation in the section at the head of Rierdon Gulch. The top of the section is on the west end of the divide at the base of the sheer cliffs of Hannan limestone.

UPPER CRETACEOUS

	Feet	Meters
Colorado shale (Blackleaf sandy member)		
29. Shale and sandstone: black fissile and some chunky shale. In middle part of unit green-tan, medium-grained sandstone in beds as much as 2 feet thick, and occasional nodules of fine-grained sandstone which contains worm tubes on upper surface. Unit weathers black, and sandstone forms ledges in shale slope.. Note: Top of measured section cut off by high-angle thrust which throws dark-gray, cherty, thick-bedded, fossiliferous Hannan limestone on black Colorado shale.	90	27.4
28. Sandstone: tan-green-gray, fine- and medium-grained, thin-bedded in lower part, thick-bedded (4 inches to 5 feet) in upper part. Weathers buff gray, stained drab tan, and forms sheer cliffs between black shale slopes. Upper surface of beds irregular and weathered rusty brown	42	12.8
27. Shale: black, fissile, some paper-thin, extremely fine-grained, smooth. Several 6-inch to 2-foot zones of greenish-weathering, calcareous, dark-gray, finely arenaceous chunky shale and sandstone; and a few small, hard, black-gray limestone concretions. Unit weathers black above upper drab-buff shale of Kootenai formation	73	22.1
Total thickness exposed of Colorado shale	205	62.3

LOWER CRETACEOUS

	Feet	Meters
Kootenai formation		
26. Shale, sandstone, and concretions: dull-green, maroon, and drab-buff, hard, chunky shale in alternating zones; and some 3- to 6-foot zones of brighter-green, thin-bedded sandstone which contains large rounded concretions of dull-green, tough, dense, dark-brown-weathering sandstone. Unit weathers green, drab tan, and maroon. Upper 5 to 7 feet drab-buff-tan-weathering chunky shale, here capped with 1- to 2-inch beds of argillaceous, limonitic sandstone	84	25.6
25. Sandstone: green, medium-grained, generally thick-bedded, massive, dense; upper beds darker-green and finer-grained. Lower half strongly cross-bedded. Much irregularly distributed limonite throughout unit. Forms cliffs	66	20.1
24. Shale and sandstone: maroon and tan-green, hard, chunky, finely arenaceous shale, and in lower 5 to 6 feet green, medium-grained sandstone. Unit weathers drab green-tan with maroon band near middle	34	10.4
23. Shale: drab-buff, very finely arenaceous, chunky, hard shale or mudstone in lower and upper parts; drab-green micaceous, arenaceous shale in middle part. Unit weathers drab tan and forms slope between cliffs	36	11.0
22. Sandstone: dull-green, medium coarse-grained, cross-bedded, thin-bedded but massive. Grains of black chert?, gray quartz, salmon-pink orthoclase, muscovite, and some augite and hornblende. Green color may result from weathering of ferromagnesian minerals. Weathers dull-green stained brown on cliff faces. This sandstone is a lens which, one-eighth mile south, thickens to 100 feet or more	45	13.7
C. S. Ross (personal communication) who studied a thin section of this rock, says: "An arkosic sandstone, or perhaps it might be called a graywacke. It is composed of angular fragments of quartz, quartzite, chert-like fragments (very abundant), feldspar, biotite, chlorite, muscovite, shale, schist, and volcanic rock grains. This is all cemented together by a pale-green material that most closely resembles celadonite."		
21. Shale: maroon and drab-buff, chunky and some very slightly fissile, some finely arenaceous. Weathers maroon and buff and forms slope between cliffs	55	16.8
20. Sandstone: dark-green-gray, massive, medium-coarse-grained, irregularly and thick-bedded, locally cross-bedded. Weathers drab brown and forms cliffs. Upper third brighter green and finer-grained	31	9.4
19. Sandstone: dull-green, micaceous, soft, thin-bedded, massive, tough, separated by 1- to 4-foot zones of dark-green-gray coarse-grained, thick-bedded, hard sandstone which forms ledges and is slightly lenticular; and contains much limonite which weathers brown on bedding surfaces. Unit weathers green gray stained brown irregularly	79	24.0
18. Shale, sandstone, and concretions: alternating zones of maroon, chunky, and fissile, finely arenaceous shale; pale green-gray shaly bedded sandstone which contains concretions of sandstone; and dark-maroon-gray, fine-grained, hard, siliceous? limestone. Many small limestone concretions covered with a layer of hematite or limonite. Unit weathers maroon, streaked gray green, and forms smooth slopes	143	43.6
17. Sandstone: green, massive, fine-grained, dense, thin-bedded; contains some brown-weathering sandstone concretions 12 inches thick. Sandstone weathers green gray and forms ledge	19	5.8

	Feet	Meters
16. Shale, sandstone, limestone, and concretions: alternating units of dull-maroon, finely arenaceous, chunky, and a little fissile shale in bands 20 to 40 feet thick; thinner zones of pale-green arenaceous, thick-bedded sandstone which locally grades into argillaceous, thin-bedded sandstone; and in middle of unit occasional beds of maroon-gray finely crystalline limestone which exhibits cone-in-cone structure. In green sandstone are many 8- to 15-inch concretions of lavender-gray, medium-grained, dense, hard, limonitic sandstone which weathers dark brown. Septaria common. Some small (1 to 3 inches) concretions of hematite mixed with limonite. Unit weathers banded maroon and green, and concretions weather dark brown	161	49.1
15. Sandstone: pale- and green-gray, fine- to medium-grained, dense, thick-bedded; weathers light-buff stained brown from limonite. Upper bed weathers deep tan and to rounded irregular surfaces	16	4.9
14. Shale: pale-olive-green, finely arenaceous shale or mudstone. In middle, 2 to 3 feet of dark-maroon and black-gray dense shale which may be manganiferous	34	10.4
13. Limestone: dove-gray, lithographic, thick- and thin-bedded (4 to 10 inches); weathers pale buff gray. Lower beds contain medium-high-spired gastropods	16	4.9
12. Quartzite and shale: black-gray, extremely fine-grained, dense, thick-bedded quartzite in lower half, and dark-gray clay-shale which weathers light gray. Quartzite weathers green-gray stained tan	12	3.7
C. S. Ross (personal communication), who studied a thin section of this quartzite, says: "A very fine-grained arkosic rock, composed dominantly of angular quartz grains, set in a very fine-grained cement of secondary quartz, and mica-like or kaolin-like minerals."		
11. Shale and arkose: alternating zones of drab arenaceous shale, and three beds of cream-gray and green-gray coarse-grained quartzite and arkose. Unit weathers buff tan	40	12.2
10. Quartzite: two beds; tan and dark-gray, coarse-grained. Grains of quartz, jasper, feldspar, garnet, and rare augite and hornblende. Contains angular pebbles of cream-tan, fine-grained quartzite ¼ to 1 inch in diameter. Unit weathers rusty tan and forms ledge	2	0.6
9. Unit covered: probably underlain by shale and shaly sandstone	38	11.6
8. Sandstone: pale-tan, fine-grained, grades up into dull-gray finely banded coarse-grained, and at top, 3 feet of cream-gray, medium-grained sandstone. All thick-bedded (2 to 36, average 18 inches). Forms cliff	10	3.0
7. Shale and sandstone: pale-drab-green, faint-maroon-gray, and some tan, more or less finely arenaceous shale which breaks to tiny angular fragments; interbedded green-tan-gray, 2- to 24-inch beds of sandstone in lower third; some tan-gray "salt and pepper" sandstone in middle third; dull-gray, fine-grained, dense, hard, finely banded thick-bedded sandstone in upper third. Sandstone forms ledges in slope and increases in amount and thickness of beds up section	90	27.5
6. Shale and limestone: black-gray, buff, and drab-green, chunky, and some fissile shale which becomes finely arenaceous up section. In lower half are 6- to 8-inch beds of blue- and pale-gray, finely crystalline, limonitic limestone which weathers tan. Shale weathers buff gray, and contains fragments of silicified wood, and fragmental bones and teeth of reptiles	24	7.3
5. Limestone: tan, thin-bedded and arenaceous in lower 6 inches; blue-gray, lithographic, hard, pure; one bed in upper 18 inches. Contains stringers of limonitic clay and weathers drab brown. Probably algal in origin	2	0.6

	Feet	Meters
4. Shale and sandstone: black-gray, chunky, very finely micaceous shale; contains 2¾-inch concretions of black limestones whose centers contain calcite crystals as much as 1 inch long. In upper part are interbedded green-tan, thin-bedded, flaggy argillaceous micaceous, fine-grained sandstones	6	1.8
3. Sandstone and shale: similar to that in unit number 2, but shale is thicker-bedded and lumpy. Weathers drab rusty gray	5	1.5
2. Sandstone and shale: dark-green-gray, fine-grained, thin- and irregularly bedded, micaceous sandstone; dark-gray, arenaceous shale interbedded. Occasional 2- to 5-inch beds of medium coarse-grained, tan and gray hard sandstone which contains limonite grains and weathers dark rusty brown. In upper part of unit are some nodules of concentrated limonite. Unit weathers black green stained rusty brown	47	14.3
1. Sandstone: one bed, faint-tan-gray, fine-grained, hard. Contains finely disseminated limonite. Weathers tan and forms ledge. More or less lenticular	1-5	0.3-1.5
Total thickness of Kootenai formation	1100	335.3

Kootenai formation.—The rocks correlated with the Kootenai formation of Dawson (1885, p. 2) vary lithologically more than any other indurated formation in the mountains and thus have been important in the structural and physiographic development of the Sawtooth Range.

The Kootenai formation contains few, if any, persistent lithologic units that can be traced throughout the mountains. Stebinger (1918, p. 156) stated that the formation is 900 feet thick in the region just east of the Sawtooth Range, and that the Kootenai: ". . . is composed essentially of shale and clay that are mostly red and purple, alternating with six to eight beds of gray to greenish-gray medium to coarse grained sandstone between 30 and 60 feet in thickness and rather evenly distributed throughout the formation."

In the Sawtooth Range the Kootenai formation also consists of alternating shales and sandstones but the sandstones are lenticular, not persistent, and are irregularly distributed throughout the formation (Pl. 3, fig. 1).

In the Rierdon Gulch section the Kootenai formation is 1100 feet thick, but the medial conglomerate is absent, and the formation appears to be thinner than in some other places in this part of the mountains. Probably the maximum thickness of the Kootenai is more nearly 1500 feet.

The lower part of the formation consists of an interbedded series of black-gray micaceous and arenaceous lumpy shales, and thick- and thin-bedded, lenticular, tan and dark-green-gray sandstones (Pl. 3, fig. 1). The unit locally is marked at the top by a 2-foot bed of tan and blue-gray hard limestone. Much limonite, locally concentrated in nodules, is disseminated throughout the shale and sandstone causing them to weather rusty brown. The remainder of the Kootenai (1035 feet) consists of

20- to 40-foot units of maroon and green-gray, micaceous, finely arenaceous, chunky and fissile shales. Thinner units of pale- and dull-green fine- to medium-grained, locally argillaceous, thin-bedded but massive soft sandstone alternate with the shales. Sandstone predominates in the upper part of the larger unit. The most striking features of the sandstones are the green color caused by the cementing mineral, which is thought by C. S. Ross (personal communication) to be celadonite (Hendricks and Ross, 1941, p. 683-708), and the wide variety of minerals which comprise the rock. (*See* unit 22 of Rierdon Gulch section.) Within some of the green sandstones in the upper-middle and near the top of the Kootenai formation are many 8- to 15-inch concretions of lavender-gray, medium-crystalline, dense, hard, limonitic sandstone which weathers very dark brown. Near the upper-middle part of the formation is a 16-foot unit of dove-gray lithographic thick- and thin-bedded limestone whose basal beds contain high-spired gastropods.

A remarkably persistent conglomerate also is present in the upper-middle part of the Kootenai in the Sawtooth Range. The pebbles range from one-eighth to 7 inches but average 1 inch in long diameter and consist of monzonite, black chert, pink quartzite, white and tan quartz, and some jasper (Pl. 3, fig. 2). The conglomerate is estimated to be nearly 100 feet thick on the ridge east of the 9100-foot peak east of Rocky Mountain.

The brilliant red colors, characteristic of the Kootenai formation in the southern part of the Sawtooth Range, are not so well developed in the central part of the range, where the formation contains more drab-green sandstone and less maroon shale.

Colorado shale.—The Colorado shale in the central part of the Sawtooth Range is represented by the Blackleaf sandy member (Stebinger, 1918, p. 158-161) which rests almost conformably on the upper shale and sandstone of the Kootenai. The Colorado shale usually is cut out by high-angle thrusts which threw limestone of the Hannan on shale and sandstone of the Kootenai. In the Rierdon Gulch section 205 feet of the Blackleaf sandy member is well exposed. The basal unit consists of 73 feet of black soft smooth fissile shale, in which are intercalated several 6- to 24-foot dark-gray-green, calcareous sandstones and a few black-gray, hard, limestone concretions. Above the basal black shale is 42 feet of tannish-green-gray, fine- and medium-grained, thin- to thick-bedded massive sandstone, which weathers drab tan and forms sheer cliffs. The youngest Colorado exposed at the head of Rierdon Gulch is 91 feet of black shale, in the middle of which are interbedded green-tan fine-grained

FIGURE 1. KOOTENAI FORMATION AT HEAD OF NO BUSINESS CREEK
Kk = Kootenai formation, Je = Ellis formation, Ch = Hannan limestone.

FIGURE 2. CONGLOMERATE IN MEDIAL PART OF KOOTENAI FORMATION
Lead pencil gives scale.

KOOTENAI FORMATION

FIGURE 1. GROUND MORAINE RESTING ON KOOTENAI FORMATION IN NORTH FORK OF SUN RIVER VALLEY
Pd = Morainal material, Kk = Kootenai formation.

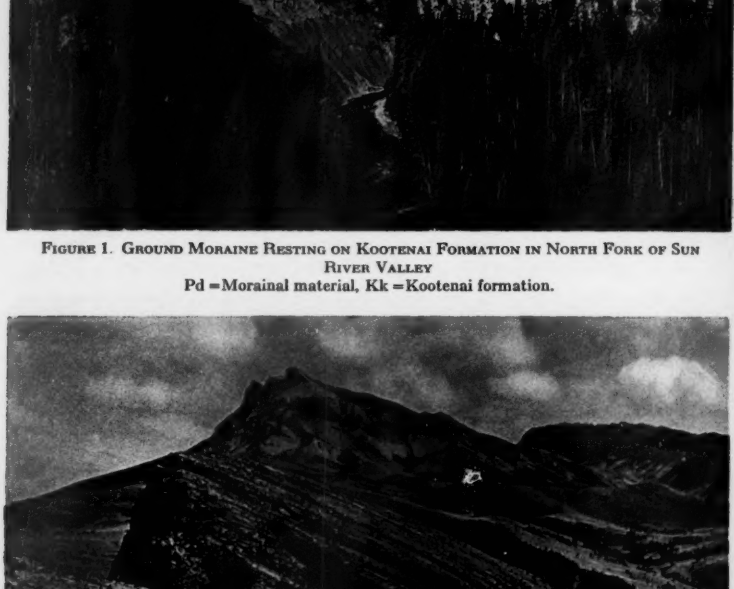


FIGURE 2. LOOKING SOUTH ALONG FRONT OF RANGE TO SAWTOOTH RIDGE

GLACIAL DRIFT ON KOOTENAI FORMATION AND FRONT OF SAWTOOTH RANGE

sandstones in beds as much as 2 feet thick; however, younger Colorado shale than that at the head of Rierdon Gulch may crop out in the central part of the Sawtooth Range. Fossils were not found in the central part of the range, but in younger beds of the Blackleaf sandy member in the southern part of the Sawtooth Range (Deiss, 1943, p. 239) the following species were collected: *Cardium* n. sp., *Corbula pyriformis* Meek var., *C.* cf. *C. nematophora* Meek, *Lingula* sp., *Nuculana* sp., *Ostrea* sp., *Pyrgulifera humerosa* Meek var., *Thracia* sp.

Igneous rocks.—The only igneous rocks in the central part of the Sawtooth Range are diorite and syenite, that were intruded as a sill now exposed on the east side of the North Fork of Sun River Valley. The sill forms a dissected ridge which descends in altitude from 7000 feet north of Cabin Creek to 6300 feet north of Headquarters Creek. The sill also thins northward and disappears on the ridge north of Headquarters Creek. The rocks are similar in composition to those forming the sills in Patrick's Basin and probably were intruded at the same time—late in the Cretaceous period (Deiss, 1943, p. 248). C. S. Ross, who studied thin sections made from rock specimens collected in 1941, comments as follows:

"The specimens vary somewhat in ratio of orthoclase to plagioclase (oligoclase). They are probably best described as diorites, although they may vary to monzonite in composition. There is a small proportion of quartz, and the essential dark minerals are augite, biotite and magnetite, which do not exceed a few percent of each."

Ross also restudied thin sections of the rock specimens collected in 1940 and compared them with new specimens collected in 1941 and with two specimens collected from the same sill identified as syenite by Adolph Knopf (Cobb, 1941, p. 10). In summary of the information obtained from the larger number of specimens and thin sections Ross (personal communication) says: "These specimens all belong to the same group, and one contains quite a proportion of plagioclase. Others contain abundant orthoclase and all are characterized by secondary biotite aggregates. Thus as a group, they seem to be syenitic as suggested by Knopf."

PLEISTOCENE DEPOSITS

Most of the mountain valleys in the central part of the Sawtooth Range contained glaciers during the Wisconsin stage. The alpine glaciers were largest near the crest of the range at the heads of the main east-west streams such as Deep, Biggs, Headquarters, Ray, and Route creeks, and at the heads of the South and Middle Forks of Teton River (Fig. 2). The ice deepened and cut the lower valleys into U-shaped profiles and sculptured imposing cirques on both flanks of the crest of the range.

Part of the debris eroded from the mountains was carried east through the valleys of Deep Creek and the Teton River and was deposited as terminal moraines on the plains in front of the mountains (Alden, 1932, p. 120). As the ice retreated at the close of the Wisconsin, ground moraines were laid down in the lower parts of many of the mountain valleys. Recessional moraines are numerous near the higher peaks, and lateral moraines were deposited on the sides of many valleys. The greatest glacier in the region was just west of the central part of the Sawtooth Range (Fig. 2) in the North Fork of Sun River Valley. The ice flowed westward out of the many valleys of the Sawtooth Range and eastward from those of the Lewis and Clark Range. Much of the North Fork Valley is covered with a veneer of ground moraine through which Recent streams have cut steep-walled canyons and exposed the underlying bedrock (Pl. 4, fig. 1). Post-Wisconsin streams also cut small but sheer-walled canyons in the glacial drift and subjacent bedrock in many of the mountain valleys (Pl. 9, fig. 2). Unfortunately, the glacial drift slumps and covers the floor over which the ice moved. East of the crest of the Sawtooth Range glacial drift is much more widespread at the head of and near the South Fork of Teton River. Likewise, the cirques cut in the crest of the range are larger than those father south. These facts indicate that larger glaciers existed in the Teton than in the Deep Creek drainage and partly explain the fact that the terminal moraine of the Teton glacier (Calhoun, 1906, p. 17) extends more than 4 miles in front of the mountains whereas that of the Deep Creek glacier extends only 2 miles (Alden, 1932, p. 120).

In the central part of the Sawtooth Range evidence was not seen which would indicate more than one stage of glaciation. The perched diorite erratics (Deiss, 1942, Pl. 2, fig. 2), so numerous in the southern part of the mountains, also are absent. The much higher crest of the range north of Deep Creek probably prevented the eastward movement of ice from the Lewis and Clark Range where the only igneous rocks west of and in the central part of the Sawtooth Range are exposed. Calhoun (1906, p. 16-17) noted the absence of diorite in the terminal moraines of the Deep Creek and Teton River glaciers in front of the mountains.

Fluvioglacial sands and gravels may have been laid down in some of the valleys such as the upper-middle part of South Fork of Deep Creek, and the South and Middle Forks of Teton River. If they were deposited they have not been recognized and may have been mapped with the Recent alluvium.

Glacial deposits rest on all the older bedrock formations in the mountains but do not blanket them from view except in some of the valleys and in relatively narrow bands on the higher ridges and peaks.

RECENT DEPOSITS

Recent alluvium is not widespread in the Sawtooth Range. Recent streams have deposited gravel, sand, and mud on some of the valley floors where the velocity was checked temporarily as the streams encountered resistant strata or were dammed by glacial drift or by beaver. The alluvium in the upper-middle part of the valley of South Fork of Deep Creek apparently resulted from temporary base-leveling of that part of the stream by the slice of Hannan limestone west of Rain Creek (Fig. 2). The flood plains in the lower part of the forks of Teton River may have been formed when the streams were retarded as they cut through the Hannan limestone in the Teton anticline. However, the alluvium in the valleys of the South and Middle Forks may have been deposited when the streams were impounded behind the terminal moraines of the Teton glacier near the mountain front.

In many of the mountain valleys Recent silts have been caught in the numerous beaver ponds which dot the valleys. Beaver are responsible for most of the alluvium in the middle and upper parts of Hannan, Blacktail, Mortimer, and Green gulches and have produced alluvial flats and large, nearly filled swamps in Biggs Creek and at various places along the east side of the valley of the North Fork of Sun River; in fact, filling of beaver dams may account for most of the alluvium which collected as graded flat planes in the valley bottoms since the retreat of the Wisconsin alpine glaciers. Beaver are plentiful in the mountains and may have been numerous during many thousands of years in this region as they seem to have been in northeastern United States (Ruedemann and Schoonmaker, 1938, p. 523-525).

The streams in most parts of the mountains today are cutting downward rapidly and are producing narrow steep-walled canyons in the valley floors. In such places the bedrock, glacial drift, and post-Pliocene alluvium are being eroded, carried eastward, and redeposited along the river valleys which cross the plains.

STRUCTURAL PROVINCES IN CENTRAL PART OF SAWTOOTH RANGE

Three regions or provinces characterized by different types of geologic structure are recognized in the central part of the Sawtooth Range (Fig. 2). For convenience in discussing the tectonic problems of the area, the three provinces are referred to as the eastern, central, and western structural provinces. The eastern structural province is characterized mainly by a series of en echelon, high-angle to moderately low-angle, westward-dipping thrusts, which extend through its central and western parts and are especially numerous and closely spaced in the northern part. The

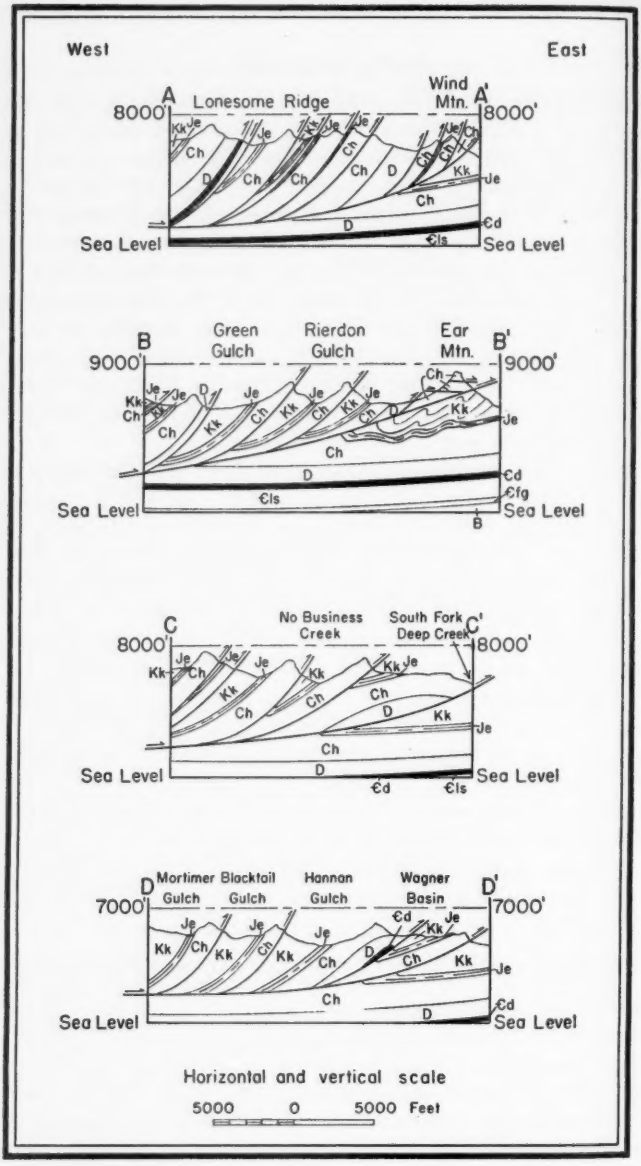


FIGURE 3.—*Structure sections across eastern structural province*

Kk = Kootenai formation, Je = Ellis formation, Ch = Hannan limestone, D = Devonian (formation unnamed), €d = Devils Glen dolomite, €ls = Cambrian limestones undifferentiated, €fg = Flathead sandstone and Gordon shale combined, B = Belt rocks.

northeastern part of this province is characterized by gently folded beds above a thrust sole. The central structural province is characterized by intense imbrication confined largely to the Hannan and Devonian rocks, and by drag-folding against the high-angle thrusts. The western structural province is characterized by folded low-angle overthrusts, and by large open folds.

The central province is separated from the eastern province by a continuous fault, or fault zone, along which Mississippian, Devonian, and, locally, Cambrian rocks were folded and thrust over the Kootenai or Colorado formations. The western province is separated sharply from the central province by a fault zone west of which the rocks are folded complexly and are thrust eastward over the Kootenai and, locally, Colorado formations. The southern extension of the western province just north and south of Sun River (Pl. 8, fig. 1) is the area in the southwestern part of the Saypo quadrangle referred to as the "Eastern belt of folding" (Deiss, 1943, p. 252).

EASTERN STRUCTURAL PROVINCE

STRUCTURE ALONG MOUNTAIN FRONT

General conditions.—The front of the Sawtooth Range is the east part of the eastern structural province and consists of a number of moderately high-angle thrust faults which strike North to N. 28° W. The faults are arranged en echelon so that the southern end of each successive thrust begins east of the preceding thrust. The mountain front is formed of Hannan limestone, which was shoved eastward along the thrusts and rode up over the Kootenai and Colorado rocks (Pl. 4, fig. 2). South of the South Fork of Deep Creek, the Hannan and overlying Ellis and Kootenai strata above the thrusts are nearly horizontal or dip gently west (Fig. 3, D-D′, east part of section). At the South Fork of Deep Creek, and generally to the north also, the Hannan limestone along the east front of the range dips to the east and is dragged into an anticline (Fig. 3, C-C′, east part of section) above the thrust surface. Locally the anticline is nearly closed and is overturned (Stebinger, 1918, Pl. 24).

Teton anticline.—The only place in which the front of the Sawtooth Range is not sheer-walled, and also is not marked by a thrust fault, is between the forks of, and 3 miles north of, the Teton River. The mountain front in this area is formed of Hannan limestone which was drag-folded into two open anticlines separated by an open syncline. Stebinger (1918, Pl. 24) called the anticlinorium thus produced the Teton anticline (Fig. 2) and indicated in his structure section (Stebinger, 1918, Pl. 24, section

along line B-B′) that the Hannan limestone was dragged along a fault that lies to the east and is covered with glacial drift.

Structure near Ear Mountain.—The geologic structure at and near Ear Mountain (Fig. 3, B-B′, east part of section) is a combination of low-angle thrusting and folding of the Devonian and Hannan limestones above the thrusts and of intense crumpling of the incompetent shales and sandstones of the Kootenai below the thrusts (Pl. 5, fig. 1).

The thrust fault which forms the sole at Ear Mountain dips more gently than any others observed in the eastern structural province (Fig. 3, B-B′, east part of section), and its eastern extension, now eroded, may have dipped east. The Hannan limestone above the lower thrust also dips gently east. When movement took place, the Hannan and upper part of the underlying Devonian limestone were broken by two nearly parallel thrusts and were shoved east over the Kootenai. Erosion cut the deep valley of the South Fork of Willow Creek which heads west of Ear Mountain where both faults are exposed. Consequently Ear Mountain is almost an erosion remnant or klippe of Hannan and Devonian limestones resting on intensely deformed shale and sandstone of the Kootenai (Pl. 5, fig. 1).

STRUCTURE WEST OF MOUNTAIN FRONT

General statement.—The belt between the thrust slices along the eastern front of the Sawtooth Range and the western edge of the eastern structural province averages 4 miles in width. The length of the belt is unknown, but it has been mapped 30 miles, from the south edge of the Saypo quadrangle, northward to the crest of the ridge north of the Middle Fork of Teton River (Fig. 2). The belt extends an unknown distance north of the Middle Fork of the Teton River. The boundary between the eastern and central structural provinces is marked by the thrust which extends northward up the west side of Mortimer Gulch, across the West Fork and up Blacktail Gulch to Deep Creek and up the west side of Erosion Creek; N. 10° W. across the head of the North Fork of Deep Creek; and 1¼ to 2¼ miles east of Rocky Mountain, Twin Peak, and Teton Peak. The boundary extends northward along the west side of the North Fork of Teton River, somewhere east of Mount Wright (Fig. 2). The structure within this narrow elongate area is composed of a series of high-angle thrusts which strike North to N. 5° E. south of the South Fork of Deep Creek and strike North to N. 18° W. north of Deep Creek.

Structure south of Deep Creek.—Between the Sun River and the South Fork of Deep Creek the thrusts are so widely spaced that only four major ones occur between Wagner Basin and Mortimer Gulch (Fig. 3, D-D′). This area contains the simplest structure in the Sawtooth Range, being

FIGURE 1. EAR MOUNTAIN FROM SOUTHWEST
Compare Figure 3, B-B'.
Kk = Kootenai formation, Ch = Hannan limestone, D = Devonian limestone.

FIGURE 2. REGION NORTH OF CABIN CREEK
Ch = Hannan limestone, D = Devonian limestone (formation unnamed), €d = Devils Glen dolomite, €la = Cambrian limestones.

EAR MOUNTAIN AND RIDGES NORTH OF CABIN CREEK

FIGURE 1. HIGH-ANGLE THRUST ON NORTH SIDE OF CANYON OF NORTH FORK OF DEEP CREEK
Kk = Kootenai formation, Je = Ellis formation, Ch = Hannan limestone.

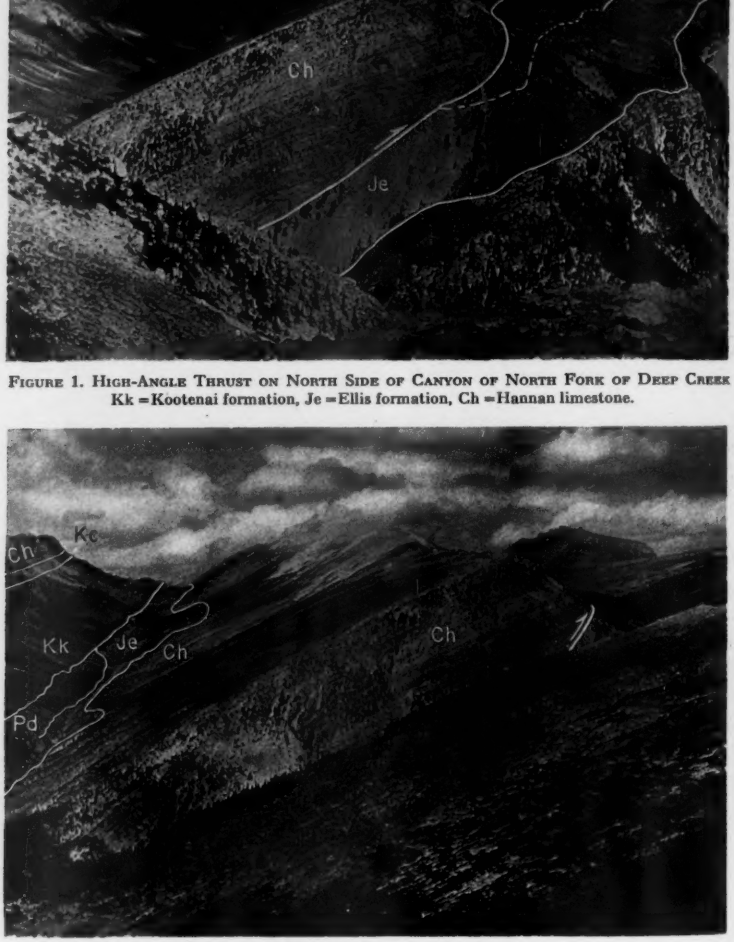


FIGURE 2. LONG STRAIGHT NORTH-SOUTH VALLEY OF SLIM GULCH
Pd = Wisconsin drift, Kc = Colorado shale, Kk = Kootenai formation, Je = Ellis formation, Ch = Hannan limestone.

NORTH SIDE OF DEEP CREEK, AND SLIM GULCH

a series of four high-angle faults along which limestones of the Hannan were thrust upon shales and sandstones of the Kootenai. The thrust on the west side of Wagner Basin is the only one that brings up Devonian rocks. The next thrust dies out northward in the mouth of Hannan Gulch and, therefore, does not appear in section D-D′ (Fig. 3). The middle and western thrusts brought up the Hannan limestone on the west side of Hannan and Blacktail gulches. The thrust which threw Devonian on Kootenai on the west side of Mortimer Gulch is the easternmost thrust of the central structural province. In this way four fault slices were formed, each consisting of a basal plate (except the Devonian limestone in part of the east thrust) of Hannan limestone overlain by Ellis and, at the top, part of the Kootenai formation. Near the surface the faults and the strata dip 35° to 70° W. (Pl. 6, fig. 1) but decrease rapidly in dip as they descend.

Structure north of Deep Creek.—From the vicinity of the forks of Deep Creek the number of thrusts increases northward until on Lonesome Ridge (Fig. 2) near the north edge of the map area nine major thrusts and five or six minor ones occur in a distance of 4 miles (Fig. 3, A-A′). As the number of thrusts increases and they are more closely spaced, the thickness of the individual thrust slices decreases, and the faults are confined to the Mississippian and Devonian limestones. This condition reaches its maximum development on Lonesome Ridge, the eastern 2¼ miles of which is formed of seven slices of Hannan and Devonian limestones. Only in three of the slices is even a thin part of the Ellis involved in the thrusting (Fig. 3, A-A′).

Because the number of slices increases northward, and because the soft sandstones and shales of the Kootenai and Ellis are eliminated or reduced in each slice, the long straight open north-south valleys (Pl. 6, fig. 2) typical of the southern part of the Sawtooth Range disappear north of the South Fork of Teton River, where they are replaced by east-west serrated ridges of Devonian and Hannan limestones.

CENTRAL STRUCTURAL PROVINCE

GENERAL STATEMENT

The central structural province is characterized by intense imbrication combined with drag-folding. This province is the narrowest of the three in the central part of the Sawtooth Range and contains the highest peaks in the range (Pl. 1, fig. 1; Pl. 7, fig. 1). The east edge of the province is marked by buff-weathering limestone of the Devonian which was dragged into open and overturned folds along the thrust which shoved the Devonian over the Cretaceous and locally over the Hannan. The widest

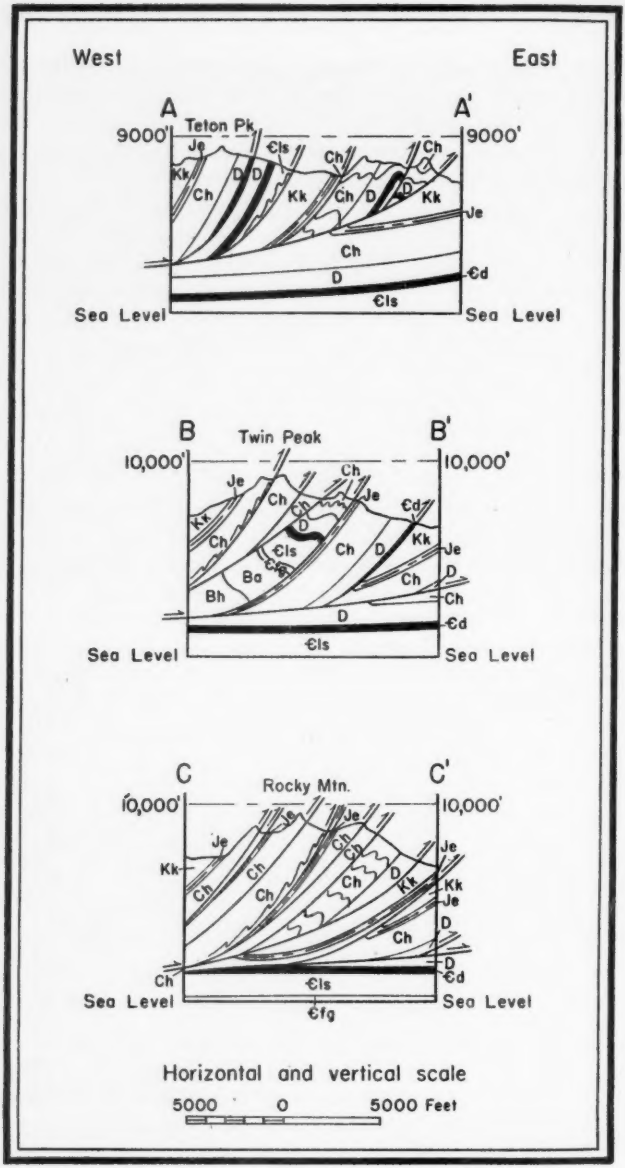


FIGURE 4.—*Structure sections across central structural province*

Kk = Kootenai formation, Je = Ellis formation, Ch = Hannan limestone, D = Devonian (formation unnamed), Cd = Devils Glen dolomite, Cls = Cambrian limestones undifferentiated, Cfg = Flathead sandstone and Gordon shale combined, Ba = Ahorn quartzite, Bh = Hoadley formation.

part of the central province is on the northeast ridge of, and includes, Twin Peak. The narrowest part of the province north of Sun River is between Mortimer and Big George gulches. The central structural province extends from the head of Mortimer Gulch northward 17 miles to Teton Peak and probably continues north into the Heart Butte quadrangle.

IMBRICATION NEAR ROCKY MOUNTAIN AND TWIN PEAK

High-angle thrusts are so closely spaced between Rocky Mountain (Fig. 4, C-C′) and the South Fork of Teton River that most of them are confined to the Hannan limestone. In this section the Hannan was broken by high-angle thrusts which flatten downward and merge with a common sole (Cadwell, 1888, p. 347-348) or soles, on which the imbricated slices of Hannan limestone rode eastward over the Kootenai. The black-and-tan lower limestone unit in many places was thrust up on the white-weathering upper dolomite of the Hannan (Pl. 1, fig. 2). At the same time, the less competent beds were mashed and dragged into broken overturned folds on the upthrown sides of the faults. Locally on Rocky Mountain and northward, the thrusting was so intense that "splinters" of Hannan limestone, 10 to 200 feet thick, developed along minor high-angle thrusts. A few of the lower beds of the Ellis formation were often caught in the fault slices and, wherever exposed, the lower soft shales of the Ellis seem to have acted as a lubricant on top of the massive dolomite of the Hannan.

As a result of the close spacing of the high-angle faults, the Hannan limestone forms nearly all the northern part of the central structural province. The ability of the Hannan limestone to resist weathering and the piling up in one place of a great mass of this limestone account for the greater height and ruggedness of the peaks (Pl. 1, fig. 1) and the position of the crest of the Sawtooth Range (Fig. 6, B-B′, central part of section). The area of intense imbrication on the crest of the range is sharply demarcated from the region of folding to the north by the head of the Middle Fork of Teton River, and by the much higher mountains in the imbricated zone.

FOLDS IN RELATION TO HIGH-ANGLE THRUSTS

General considerations.—Southeast of Rocky Mountain, and south and east of Twin Peak (Fig. 4, B-B′), the limestone and shale of the Devonian are dragged into overturned anticlines on the upthrown side of the faults (Pl. 7, fig. 1). On the east spurs of Twin Peak, the Hannan limestone also is folded into anticlines and synclines which locally are faulted on the crest and contain many minor drag-folds.

Structure east of Teton Peak.—East and southeast of Teton Peak (Fig. 2) the thrusts are more widely spaced (Fig. 4, A-A′), have a larger displacement, and involve Cambrian, Devonian, and Mississippian rocks. As the faults become larger, the closely packed imbrication gives way to folding. The resultant structure of the north part of the central province at Teton Peak is a series of three slices composed of Cambrian to Mississippian strata. The beds were folded as they were dragged against the underlying slices along the fault surfaces (Pl. 7, fig. 2). Thus, in the northern part of the central province, folding and faulting are more nearly of equal importance.

WESTERN STRUCTURAL PROVINCE

LOCATION

The western structural province includes the west-central part of the Sawtooth Range north of Sun River to beyond Route Creek (Fig. 2). The province has been mapped from its south end to Route Creek, a distance of 25 miles. The western province averages 2½ miles in width but narrows to 1¾ miles at the head of Circle Creek and to approximately 1⅛ miles at the Sun River (Pl. 8, fig. 1). The east edge of the province is marked by a fault that extends nearly due north along the west side of Big George Gulch, and across the head of the West Fork of Blacktail Gulch, and along the west side of the South Fork of Deep Creek; from there it extends N. 15° to 20° W. across the upper parts of Biggs, Headquarters, Ray, and Route creeks (Fig. 2). The western province continues north of Route Creek an unknown distance toward (probably into) the Heart Butte quadrangle. Most of the eastern edge of the western structural province is marked by open and overturned folds where the rocks were dragged against the fault along which Cambrian to Mississippian beds were thrust eastward over Kootenai or Colorado. The west edge of the western province consists of the Hannan limestone which forms the west side of the central part of the Sawtooth Range (Fig. 2).

The western province contains the most complex structures yet mapped in the Sawtooth Range. In the northern part of the province, the structure is so complex that it must be explained by two periods or stages of deformation. The structure of the western province may be characterized best as a series of low-angle thrusts and open to closed and overturned folds which affected Cambrian to Mississippian rocks.

STRUCTURE SOUTH OF CIRCLE CREEK

The area just south of Circle Creek contains the simplest geologic structures in the western province. Steamboat and locally Pagoda limestone was thrust over the Kootenai along a moderately high-angle west-

FIGURE 1. NORTH TO ROCKY MOUNTAIN SHOWING SLICES OF HANNAN LIMESTONE AND OVERTURNED ANTICLINE IN DEVONIAN AND LOWER HANNAN LIMESTONES
Ch = Hannan limestone, D = Devonian limestone (formation unnamed).

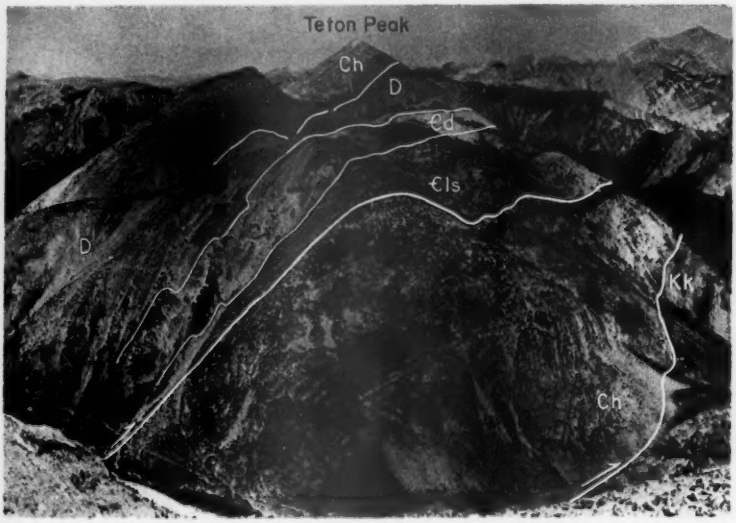


FIGURE 2. FOLDS IN DEVILS GLEN DOLOMITE AND HANNAN LIMESTONE SOUTHEAST OF TETON PEAK
Kk = Kootenai formation, Ch = Hannan limestone, D = Devonian limestone (formation unnamed), Ed = Devils Glen dolomite, Els = Cambrian limestones.

ROCKY MOUNTAIN AND TETON PEAK

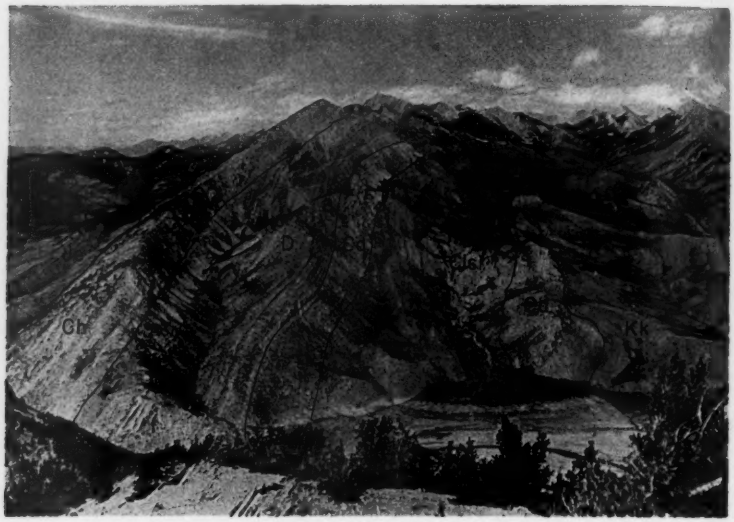


FIGURE 1. SOUTH END OF WESTERN PROVINCE AT BIG GEORGE GULCH
Kk = Kootenai formation, Je = Ellis formation, Ch = Hannan limestone, D = Devonian limestone (formation unnamed), €d = Devils Glen dolomite, €ls = Cambrian limestones.

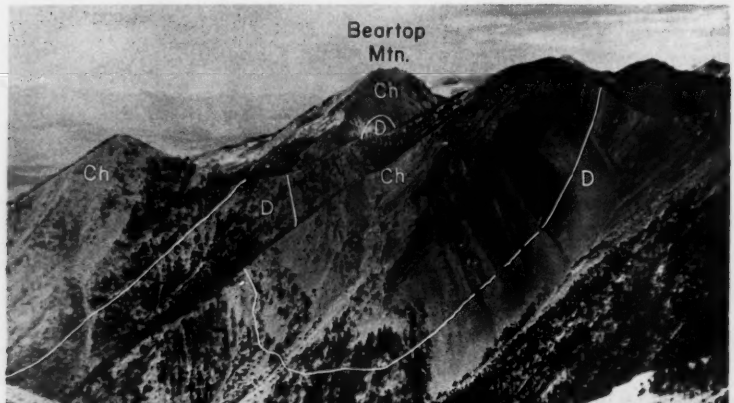


FIGURE 2. LOOKING NORTH ACROSS GROUSE CREEK, SHOWING BEARTOP ANTICLINE AND GROUSE CREEK SYNCLINE
Ch = Hannan limestone, D = Devonian limestone (formation unnamed).

RIDGES WEST OF BIG GEORGE GULCH AND NORTH OF GROUSE CREEK

ward-dipping fault at the east edge of the province on the west side of Big George Gulch. The Cambrian limestone and overlying Switchback shale were dragged into an overturned anticline. Within the anticline the soft incompetent shales and limestones were thrown into overturned folds and much sheared, but the secondary folding did not affect the more competent Devils Glen and younger formations. When the thrusting and folding occurred, the Devils Glen, Devonian, and Hannan formations undoubtedly were folded against the fault as part of the major anticline, but they were subsequently removed by erosion. The Devonian and Mississippian strata strike N. 10° W. and dip 55° to 58° W. on the west limb of the truncated fold which forms the west side of the province.

FOLDS AND THRUSTS NORTH OF CABIN CREEK

General considerations.—North of Cabin Creek (Fig. 2), the folding in the western province is much more pronounced than it is farther south (Fig. 5, C-C′, east part of section). The Cambrian rocks exposed in the nose of the overturned anticline, described from the area south of Circle Creek, is exposed north of Cabin Creek and shows that the axis plunges gently southward. At Cabin Creek the west limb of the fold, formed of Devonian limestone, is broken by a high-angle thrust which threw Devils Glen dolomite on Devonian limestone (Pl. 5, fig. 2). North of Cabin Creek the fault dies out and closely parallels the axis of the fold which continues northward to the ridge between Headquarters and Ray creeks. This fold is named the Beartop anticline and is described under that heading.

The east limb of the anticline just north of Cabin Creek is also the west limb of a syncline in Steamboat to Hannan limestones. On the ridge between the heads of Cabin and Grouse creeks, several hundred feet of the lower part of the Hannan limestone marks the center of the syncline (Pl. 5, fig. 2). This syncline continues northward more than 11 miles to the ridge between Headquarters and Ray creeks and parallels the Beartop anticline throughout. This fold is named the Grouse Creek syncline, and north of Cabin Creek it plunges gently northward to Grouse Creek (Pl. 8, fig. 2).

The east limb of the Grouse Creek syncline north of Cabin Creek is the west limb of a slightly overturned anticline, which is locally squeezed and faulted along its crest, so that southeast of the head of Grouse Creek the Switchback and Steamboat formations are pinched out and the Devils Glen lies against Devils Glen (Fig. 5, C-C′, east part of section). Just north of the head of Cabin Creek a high-angle thrust threw Devils Glen dolomite on limestones of the Devonian which are intensely folded and

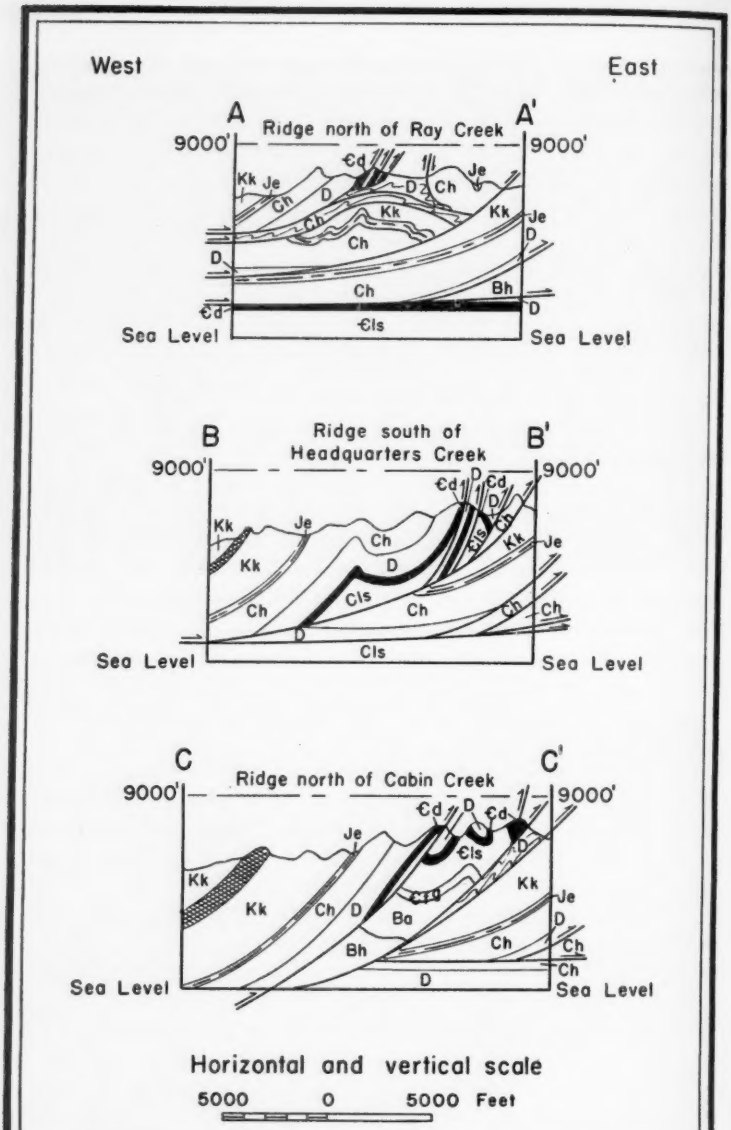


FIGURE 5.—*Structure sections across western structure province*

Kk = Kootenai formation, Je = Ellis formation, Ch = Hannan limestone, D = Devonian (formation unnamed), Cd = Devils Glen dolomite, Cls = Cambrian limestones undifferentiated, Cfg = Flathead sandstone and Gordon shale combined, Ba = Ahorn quartsite, Bh = Hoadley formation, cross-hatched pattern = sill of diorite.

mashed and are in turn thrust eastward over Colorado shale at the head of the South Fork of Deep Creek. The stratigraphic and structural relationships observable in the area strongly suggest that the Cambrian to Mississippian beds were folded into a series of two anticlines separated by a syncline at the time the folded mass was shoved east along an overthrust. As deformation continued, the beds broke to form minor high-angle thrusts along the crest of the southern part of the Beartop anticline, and just east of the crest of the eastern anticline. At the same time, the Devonian and soft Cambrian beds were dragged and sheared along the thrusts and between the competent massive limestones. After deformation ceased, erosion removed the Hannan, Devonian, Devils Glen, and Switchback from the crest of the eastern overturned and faulted anticline so that now the structure appears as a smashed mass of Devils Glen dolomite thrust over a separate slice of Devonian (Fig. 5, C-C′).

On the east side of the 8300-foot peak at the head of Grouse Creek (Fig. 2), the Devonian limestone east of the Devils Glen dolomite was folded. The folding occurred when the rocks were thrust eastward over the Colorado shale and consists of a large recumbent syncline and two anticlines separated by a smaller syncline.

Deformation during the Laramide Revolution produced increasingly complex geologic structures northward in the western structural province. The rocks between Biggs and Route creeks are more deformed and broken than they are farther south. Not only are the folds more numerous and secondarily flexured, but some of the faults are low-angle overthrusts, and these also were folded. The structures, therefore, are the most complex and difficult of interpretation thus far seen in the Sawtooth Range (Fig. 5, A-A′).

Beartop anticline.—The west side of the Sawtooth Range from Grouse Creek northward to the ridge north of Headquarters Creek is formed by the west side of a large anticline of Hannan limestone. The crest of the anticline lies just east of the crest of Beartop Lookout (B.M. 8090), for which the anticline is named (Pl. 8, fig. 2). Between Biggs and Headquarters creeks, the anticline is formed of Hannan limestone at the surface of the earth, but north of Headquarters and south of Biggs Creek the upper limestones and shales of the Devonian are exposed. The crest of the Beartop anticline is very sharp throughout its northern part and between Headquarters and Biggs creeks is broken by a high-angle thrust of small displacement (Pl. 9, fig. 1). The Beartop anticline, more than 9 miles long, is the major geologic structure on the west side of the central part of the Sawtooth Range. Measured from the Ellis-Hannan contact

at the west side of the fold to the axis of the Grouse Creek syncline on the east, the Beartop anticline averages almost 0.7 mile in width. The west limb ranges in dip from 36° near the crest to 71° W. at the Ellis-Hannan contact. The east limb of the anticline at Beartop and south to Biggs Creek (Pl. 9, fig. 1) is much steeper, the beds dipping from 70° to 80° E.

Grouse Creek syncline.—The Grouse Creek syncline lies east of the Beartop anticline, and its northern end also lies on the ridge north of Headquarters Creek. From Grouse Creek to the northern end of the syncline, the youngest beds exposed in the trough of the fold are Hannan limestones (Pl. 8, fig. 2). On the ridge three-fourths of a mile southeast of Beartop, the Ellis formation is complete, and the center of the syncline is marked by the lower sandstones and shales of the Kootenai. The dip of the beds varies widely at different places along the fold. The Grouse Creek syncline is open and probably is upright throughout most of its length, but on the ridge southeast of Beartop the syncline is overturned sharply to the east.

On the east limb of the syncline a complete section of the Devonian rocks and Devils Glen dolomite are exposed. Locally, as just north of Biggs Creek, the Switchback shale and upper part of the Steamboat limestone also are exposed. The east limb is cut off by a high-angle thrust which threw Steamboat, Switchback, or Devils Glen on Devonian (Fig. 5, B-B′). East of this thrust, the younger Middle Cambrian formations and part of the Devonian rocks are folded into closed synclines and anticlines broken by small high-angle thrusts, and the entire mass is thrust eastward over Hannan limestone or over the Kootenai or Colorado.

Folded low-angle overthrusts.—Between Ray and Route creeks, and also in Biggs Creek (Fig. 2), occur the shallowest and most complex structures in the western province (Fig. 5, A-A′). Two low-angle overthrusts were formed at two different periods or phases of the Laramide orogeny. Along the first or older overthrust, a plate of Hannan limestone and the overlying Ellis and Kootenai formations was shoved eastward over Kootenai and Ellis. The original dip of this thrust is unknown, but it must have been low. Shales, limestones, and sandstones of the Kootenai and Ellis were dragged into a series of folds when the thrusting occurred, or else these Mesozoic rocks were folded beneath the more competent thrust plate of Hannan limestone when it and the overthrust were folded.

The stress which produced the second low-angle fault thrust limestone of the Devonian and Cambrian eastward over the plate of Hannan limestone which had ridden eastward on the first thrust. The two low-angle

FIGURE 1. BEARTOP ANTICLINE
Looking south from Beartop Lookout. Only Hannan limestone shown.

FIGURE 2. POST-PLEISTOCENE CANYON IN LOWER PART OF SLIM GULCH
Pd = Wisconsin glacial drift, Je = Ellis formation, Ch = Hannan limestone.

BEARTOP ANTICLINE AND POST-PLEISTOCENE CANYON IN SLIM GULCH

thrust surfaces probably are subparallel throughout much of their length (Fig. 5, A-A′).

The cause or the mechanism that produced the folded thrusts in the western province is not yet understood because sufficient field data are not available. It seems reasonably clear, however, that these thrusts and the other structures in the central part of the Sawtooth Range had a different origin from those in the foothills of west-central Alberta recently described by Hake, *et al.* (1942, p. 301-333). The faults and drag-folds in Alberta occur solely in incompetent Mesozoic rocks and are attributed to excessive shortening in the incompetent younger strata on the gentler limb of an asymmetric syncline as a result of the growth of a competent asymmetric contiguous anticline on the west. In the Sawtooth Range, however, more of the competent Paleozoic than the incompetent Mesozoic rocks are involved in the faulting, and a large anticline is not developed in the area west of the folded faults.

Structures above the low-angle overthrusts.—The Devonian limestones above the second low-angle overthrust were dragged into a number of anticlines and synclines, and on the ridge south, and also probably north, of Ray Creek were underthrust beneath the overlying Hannan limestone. The Hannan limestone east of the underthust Devonian was bent into an open syncline and shoved eastward over the Kootenai along the thrust fault which forms the boundary between the west and central structural provinces.

North of Ray Creek, the Devils Glen dolomite and overlying basal Devonian shale and shaly limestone were broken by three high-angle thrusts that rode eastward on a sole which dips west and merges with the younger folded low-angle overthrust (Fig. 5, A-A′). The parallelism of the folded low-angle thrusts suggests that the thrusts were folded after both of them were completed. Probably the thrusts were folded during the final stresses of the Laramide orogeny immediately following the thrusting, but they may have been folded much later during the Pliocene uplift of the region, as was the Bannock overthrust in Idaho (Mansfield, 1927, p. 203).

The deep canyon of Ray Creek is cut through the entire structure down to the folded Ellis and Kootenai below the first or lower folded overthrust. Thus the canyon exposes two concentric windows in the faults. Within the inner window the Ellis and Kootenai are exposed, and within the outer window the older or first thrust plate of Hannan limestone is exposed. Higher on the north wall of the canyon, the three high-angle thrusts are completely exposed as is also the junction of the sole, from which they arise, with the younger low-angle overthrust.

SUMMARY OF GEOLOGIC STRUCTURE IN CENTRAL PART OF SAWTOOTH RANGE

The central part of the Sawtooth Range is divisible into three structural provinces which are separated by pronounced faults and characterized by distinct types of deformation. These provinces are the result of the distribution of the intensity of the stresses during the Laramide or Rocky Mountain Revolution. The intensity of the stresses apparently was greater in the northern and western parts of the map area and reached a maximum along an east-west belt between the South and Middle Forks of Teton River and between Route and Headquarters creeks (Fig. 6, A-A′).

The stresses were least intense in the eastern structural province, and the resulting deformation is less complex than elsewhere in the southern and central parts of the Sawtooth Range (Fig. 6, east part of sections). The structure there consists of a series of five to eight high-angle westward-dipping thrust faults which broke Devonian to Cretaceous strata into a series of imbricated blocks in which the beds were tilted west and, near the mountain front, gently or tightly folded. Faults are the dominant structures in the eastern province, the only folds present being local and incidental to the faults. The faults strike N. 5° to 15° E. in the southern part and due North to N. 15° W. in the northern part of the map area, and are bowed slightly northeast, the inside of the bow being upthrown. Throughout most of their length the movement on the faults apparently was dip-slip. The strike of the faults parallels the strike of the strata. The fault surfaces dip 35° to 70° at the earth's surface but probably flatten rapidly with depth. The eastern thrusts along the mountain front seem to dip less steeply than those farther west in the eastern structural province (Fig. 6, east part of sections).

The stresses in the north part of the central structural province resulted in much more intense deformation than in the southern part of the province. As in the eastern province, the high-angle thrusts in the southern part of the central province are fewer than farther northward, and the rocks were not drag-folded. The most intense high-angle thrusting and drag-folding in the central part of the Sawtooth Range occurred in the northern part of the central province (Fig. 6, A-A′, central part of section). Along the crest of the range between the heads of Biggs Creek and the Middle Fork of Teton River, the high-angle faulting is largely confined to the Hannan limestone which locally was splintered by minor thrusts, the splinters or wedges being 10 to several hundred feet thick. Because the Hannan and underlying Devonian limestones were mashed and folded during the movement, faults and minor drag-folds are of more nearly equal importance in the northern part of the central structural province (Pl. 7, figs. 1, 2).

The western structural province contains more diversified types of geologic structure than either the central or eastern provinces. As in the other two, however, the stresses were most intense in the northern part and produced the most complex deformation in the range. Even in the

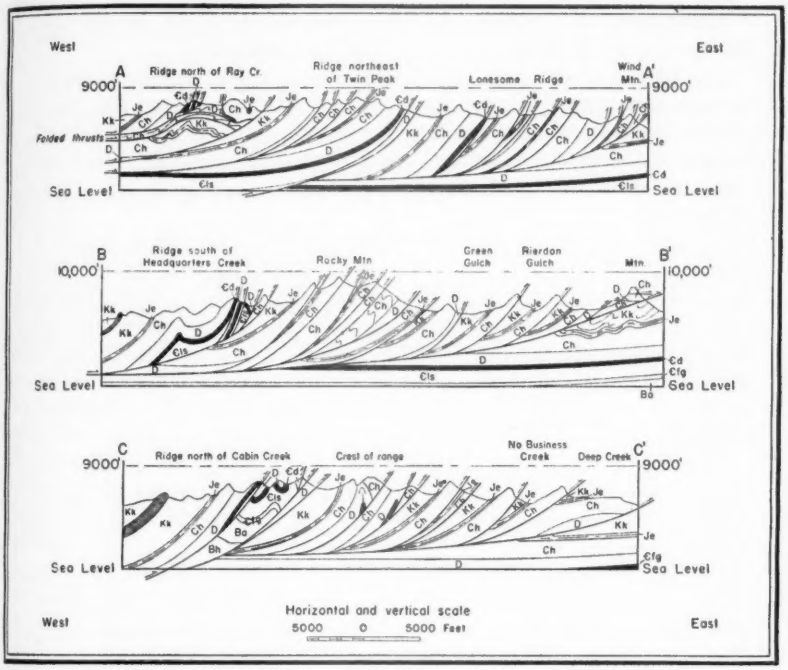


FIGURE 6.—*Structure sections across central part of Sawtooth Range*

Kk = Kootenai formation, Je = Ellis formation, Ch = Hannan limestone, D = Devonian (formation unnamed), Cd = Devils Glen dolomite, Cls = Cambrian limestones undifferentiated, Cfg = Flathead sandstone and Gordon shale combined, Ba = Ahorn quartzite, Bh = Hoadley formation, cross-hatched pattern = sill of diorite.

southern part of the western province the rocks were much more deformed than in the southern part of the central and eastern provinces. In contrast with the other provinces, the western province is characterized by open and closed folding of the strata above low-angle instead of high-angle overthrusts. Although the rocks are broken by high-angle thrusts along the eastern side of the province, the only imbricate structure observed in the province occurs between Route and Ray creeks (Fig. 5, A-A', central part of section).

In addition to the large open folds, such as the Beartop anticline and the Grouse Creek syncline (Pl. 5, fig. 2; Pl. 9, fig. 1), two other structures are known in the Sawtooth Range from the western province only: folded low-angle overthrusts, and an underthrust north of Headquarters Creek (Fig. 5, A-A′).

In summary, the geologic structures in the central part of the Sawtooth Range may be tabulated in order of their abundance:

(1) High-angle dip-slip strike faults are the most prominent and important phenomenon in the range. These faults probably all decrease in dip as they descend, and merge with one or more soles along which the imbricated fault blocks rode eastward (Fig. 6, all sections). The low-angle thrusts exposed along the mountain front seem to be the eastern end of the soles.

(2) Open, closed, upright, and recumbent drag-folds (Pl. 7, figs. 1, 2) occur in the northern and western parts of the map area in the Sawtooth Range (Fig. 6, A-A′ and B-B′, west part of sections). In many places the crests of the folds were broken by small thrusts, and in others the rocks were mashed. The confining pressure, however, was not great enough to metamorphose the sediments. The absence of regional metamorphism in an area in which great lateral movement occurred strongly supports the conclusion that the rocks were deformed only in a shallow layer.

(3) Open folds, formed independently of drag along faults, were produced in the western third of the central part of the Sawtooth Range (Pl. 8, fig. 2). These large folds locally were broken along the crest and also exhibit secondary flexures.

(4) Folded low-angle overthrusts occur in the northern part of the western structural province and indicate that the Laramide orogeny consisted of two pulses or phases in the central part of the Sawtooth Range. The thrusts at Ear Mountain (Pl. 5, fig. 1) may have been folded, but the evidence is not clear.

(5) The only underthrust in the area is of doubtful significance, because it is nearly vertical (Fig. 5, A-A′, east part of section). This fault is near the eastern edge of the western province, and along it the upper shales and limestones of the Devonian were mashed, folded, and thrust under a synclinal fold of Hannan limestone which in turn rode east upon the Kootenai formation along a high-angle thrust.

PRE-PLEISTOCENE HISTORY OF SAWTOOTH RANGE

GENERAL CONSIDERATIONS

All the geologic structures in the Sawtooth Range seem to have been formed during the Laramide Revolution which probably took place some time between the cessation of deposition of the St. Mary River formation

(Upper Cretaceous) and before the end of the Eocene (Alden, 1932, p. 7-8). At the beginning of the Oligocene the streams east of the mountains were established on the Cypress Plain (Alden, 1932, p. 4) and at their heads were cutting westward into the mountains. The peaks in the Sawtooth Range as well as those in the Lewis and Clark Range to the west exhibit an accordance of summit level which suggests that the mountains were at least partly peneplained during the Oligocene, Miocene, and early part of the Pliocene. Another factor which strongly indicates mature erosion of the Sawtooth Range is the position of the largest streams which, in the range, flow eastward directly across the strike of the ridges and form deep canyons in the limestones. How nearly base-leveled the range was is unknown, but that the main streams originally must have been established on a plain seems inescapable.

LATE TERTIARY UPLIFT

Late in the Pliocene or possibly early in the Pleistocene (Alden, 1932, p. 31), the entire area of the northern Rocky Mountains was elevated bodily, possibly several thousand feet. As the mountains rose, the main streams were able to maintain their courses on the plain then at its most mature stage. The absence of deformation in the Sawtooth Range since the Laramide Revolution, except possibly the flexuring of the low-angle overthrust fault surfaces, indicates that the Pliocene rejuvenation of the northern Rocky Mountains was an epeirogenic movement. Apparently, the region now occupied by the Sawtooth, Lewis and Clark, and Flathead ranges, and by the Northern Great Plains east of the mountains was elevated bodily but differentially, the western part which contains the mountains, probably being raised more than the Plains. Whether or not the uplift consisted of one or of several movements is unknown. The fact that the main eastward-flowing streams were able to maintain their courses indicates that the uplift was slow and of long duration.

The old Eocene mountains undoubtedly were not completely base-leveled by late Pilocene time but were degraded maturely. The area now occupied by the Sawtooth Range probably was a series of low rolling ridges whose rounded crests were formed of Hannan limestone. Local peaks must have stood above the mean level of the region and, then as now, probably were near the crest of the range. Rocky Mountain, Twin Peak, Mount Wright, and others of the higher peaks today may well represent remnants of old peaks which early in the Pliocene stood 500 to 1100 feet above the partly completed but rolling plain.

QUATERNARY HISTORY OF SAWTOOTH RANGE

As the Northern Rocky Mountains in Montana were re-elevated at the end of the Tertiary, the streams began to cut downward. Probably the

tributaries of the main east-west trending streams in the Sawtooth Range were established in their present positions, being controlled then as now by the geologic structure of the mountains. When the region was elevated the rejuvenated streams were accelerated and began to cut downward and headward. North and south of the Sun River the tributary streams must have rapidly removed large volumes of the soft shales and sandstone of the Ellis and Kootenai formations, and thereby left the more resistant Hannan limestone stand as high, rounded ridges between the stream valleys. In this way the long north-south valleys, characteristic of the southern part of the map area (Pl. 6, fig. 2), were located and partly completed before the Wisconsin stage of alpine glaciation began in the Sawtooth Range.

At least once, and possibly twice, during Wisconsin, ice collected in most of the valleys and soon began moving toward the main east-west valleys. The ice easily deepened the headward part of the tributary valleys, steepened their walls, and carved them into typical U-shaped profiles. Part of the debris eroded from the mountain valleys was carried east and deposited as terminal moraines on the plains just east of the mountain front (Alden, 1932, p. 120). At their heads the glaciers cut cirques on the peaks and thus produced much of the rugged topography exhibited by the Sawtooth Range.

Near the close of the Wisconsin, when the glaciers began to melt and retreat up the valleys, they deposited variable thicknesses of drift in the form of recessional and ground moraines which blanketed the bedrock floor of the valleys. In some of the valleys such as Bear, Big George, and Rierdon gulches, the morainal material dammed the lower part of the valleys and forced the temporarily impounded glacial waters to spill out into the main streams over the Hannan limestone.

Before the dams could be removed, the streams had cut narrow steep-walled canyons in the limestone, and they still flow through the Hannan limestone as they leave the broad upper valleys and enter the Sun and Teton rivers.

Since the retreat of the Wisconsin glaciers, Recent streams, particularly in the tributary valleys, are cutting narrow V-shaped canyons in the ground moraines and underlying bedrock (Pl. 9, fig. 2). Alluvium is being deposited in some of the valleys where the streams have been dammed by talus, by local harder beds, or by beaver.

The present topography of the Sawtooth Range, therefore, is the result of structural control exerted on the Pleistocene and Recent streams whose valleys were deepened and altered by Wisconsin glaciers, which also sculptured the higher peaks and ridges into their present shapes.

CONCLUSIONS

The following conclusions concerning the structure of the central part of the Sawtooth Range may be briefly summarized.

(1) Most, if not all, of the deformation which resulted in the geologic structures in the central part of the Sawtooth Range probably occurred during the Laramide Revolution.

(2) The stresses acted from the west and produced much lateral movement, but the movement was confined to the outer part of the lithosphere. The great amount of lateral movement and the shallowness of the affected zone are among the most remarkable tectonic characteristics of the Sawtooth Range.

(3) The younger Middle Cambrian, Upper Devonian, Mississippian, Upper Jurassic, and Cretaceous formations were broken by high-angle thrusts, tilted westward, and locally folded (Fig. 6, all sections).

(4) In the eastern part of the range, the strata were least affected and were broken only into a series of imbricated slices which rode eastward on a low-angle thrust sole or soles (Fig. 3, D-D′).

(5) In the central part of the range, deformation was more intense than in the eastern part. The result is closer-spaced high-angle thrusts and narrower imbricated slices composed largely of Devonian and Hannan limestones, which locally were dragged into recumbent folds on the upthrown sides of the thrust slices (Fig. 4, A-A′).

(6) Deformation was greatest in the western part of the range, where folded low-angle overthrusts, open and closed folds, and a few high-angle thrusts above the folded thrusts were developed (Fig. 5, A-A′).

(7) The southern and eastern parts of the Sawtooth Range are characterized by high-angle thrusts, and the western and northern parts of the range are characterizd by a combination of thrusting and flexuring (Fig. 6; *compare* all sections).

(8) Erosion during the Tertiary probably reduced the mountains to a rolling surface of little relief on which were established the main streams which flowed east.

(9) The late Pliocene or possibly early Pleistocene uplift was epeirogenic, caused the present height of the mountains, but probably did not produce any new structures.

(10) Pleistocene and Recent streams and Pleistocene glaciers carved the existing peaks and valleys and are responsible for the present topography of the Sawtooth Range.

REFERENCES CITED

Alden, W. C. (1932) *Physiography and glacial geology of eastern Montana and adjacent areas*, U. S. Geol. Survey, Prof. Paper 174, 133 pages, 51 Pls., 19 Figs.

Cadell, H. M. (1888) *Experimental researches in mountain building,* Royal Soc. Edinburgh, Tr., vol. 35, p. 337-357, il.

Calhoun, F. H. H. (1906) *The Montana lobe of the Keewatin ice sheet,* U. S. Geol. Survey, Prof. Paper 50, 62 pages, 7 Pls., 31 Figs.

Clapp, C. H. (1932) *Geology of a portion of the Rocky Mountains of northwestern Montana,* Mont. Bur. Mines Geol., Mem., no. 4, 30 pages, map.

Cobb, E. H. (1941) *Geology of the Gibson Lake region, Montana,* unpublished M.A. thesis, Yale Univ., 25 pages, 6 Pls.

Crickmay, C. H. (1936) *Study in the Jurassic of Wyoming,* Geol. Soc. Am., Bull., vol. 47, p. 541-564.

Dake, C. L. (1921) *Episodes in Rocky Mountain orogeny,* Am. Jour. Sci., 5th ser., vol. 1, p. 245-254.

Dawson, J. W. (1885) *On the Mesozoic floras of the Rocky Mountain region of Canada,* Science, vol. 5, p. 531-532.

Deiss, Charles (1933) *Paleozoic formations of northwestern Montana,* Mont. Bur. Mines Geol., Mem., no. 6, 51 pages, 3 Pls. (Mimeographed).

——— (1939a) *Cambrian stratigraphy and trilobites of northwestern Montana,* Geol. Soc. Am., Spec. Paper 18, 135 pages, 18 Pls., 7 Figs.

——— (1939b) *Cambrian formations of southwestern Alberta and southeastern British Columbia,* Geol. Soc. Am., vol. 50, p. 951-1026, 8 Pls., 6 Figs.

——— (1940) *Lower and Middle Cambrian stratigraphy of southwestern Alberta and southeastern British Columbia,* Geol. Soc. Am., Bull., vol. 51, p. 731-794, 5 Pls., 6 Figs.

——— (1941) *Cambrian geography and sedimentation in the central Cordilleran region,* Geol. Soc. Am., Bull., vol. 52, p. 1085-1116, 10 Figs.

——— (1943) *Stratigraphy and structure of southwest Saypo quadrangle, Montana,* Geol. Soc. Am., Bull., vol. 54, p. 205-262, 5 Pls., 3 Figs.

Hake, B. F., Willis, Robin, and Addison, C. C. (1942) *Folded thrust faults in the foothills of Alberta,* Geol. Soc. Am., Bull., vol. 53, p. 291-334, 17 Figs.

Hendricks, S. B., and Ross, C. S. (1941) *Chemical composition and genesis of glauconite and celadonite,* Am. Min., vol. 26, no. 12, p. 683-708, 1 Pl.

Knowlton, F. H. (1907) *Description of a collection of Kootenie plants from the Great Falls coal field of Montana,* Smithson. Misc. Coll., vol. 50, p. 105-130, Pls. 11-14.

Mackenzie, J. D. (1922) *The historical and structural geology of the southernmost Rocky Mountains of Canada,* Royal Soc. Canada, Tr., 3d ser., vol. 16, sec. 5, p. 97-132.

Mansfield, G. R. (1927) *Geography, geology, and mineral resources of part of southeastern Idaho,* U. S. Geol. Survey, Prof. Paper 152, 409 pages, 63 Pls., 46 Figs.

Peach, B. N., Horne, John, Gunn, W., and Hinxman, L. W. (1907) *The geological structure of the north-west highlands of Scotland,* Geol. Survey Great Britain, Mem., 668 pages, 52 Pls., 66 Figs., (map).

Reeside, J. B., Jr. (1919) *Some American Jurassic ammonites of the genera* Quenstedticeras, Cardioceras, *and* Amoeboceras *Family Cardioceratidae,* U. S. Geol. Survey, Prof. Paper 118, 64 pages, 24 Pls.

Richardson, G. B. (1913) *The Paleozoic section in northern Utah,* Am. Jour. Sci., 4th ser., vol. 36, p. 406-416.

Ruedemann, Rudolf, and Schoonmaker, W. J. (1938) *Beaver-dams as geologic agents,* Science, n. s., vol. 88, no. 2292, p. 523-525.

Sanderson, J. O. G. (1931) *An Ellis (Upper Jurassic) section at East Butte, Sweetgrass Hills, Montana,* Am. Assoc. Pet. Geol., Bull., vol. 15, p. 1157-1160, 6 Figs.

Stebinger, Eugene (1918) *Oil and gas geology of the Birch Creek-Sun River area, northwestern Montana,* U. S. Geol. Survey, Bull., no. 691-E, p. 149-184, Pl. 24, Figs. 32-34.

Willis, Bailey (1902) *Stratigraphy and structure, Lewis and Livingston ranges, Montana,* Geol. Soc. Am., Bull., vol. 13, p. 305-352, Pls. 48-53, 5 Figs.

Montana State University, Missoula, Montana.

Manuscript received by the Secretary of the Society, January 4, 1943.
Presented before the Geological Society, December 30, 1941.
Published by permission of the Director, U. S. Geological Survey.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 54, PP. 1169-1194 AUGUST 1, 1943

APPLICATION OF GEOLOGY TO THE PRINCIPLES OF WAR

BY CHARLES E. ERDMANN

CONTENTS

	Page
Abstract	1169
Introduction	1170
Acknowledgments	1171
Definitions	1171
Development of military geology	1176
Comparison of military and scientific thought	1182
Terrain	1183
Correlation of terrain with the principles of war	1186
Relation of geology to the principles of war	1189
Qualifications of the military geologist	1190
Summary and conclusions	1191
References cited	1191

ABSTRACT

This article surveys the employment of geology in war with special reference to its tactical application. Approaching the subject theoretically, from a military rather than an academic viewpoint, the first problem examined is whether our present undistinguished use of geology in war results from some inapplicability inherent in the science itself, or whether a more rational analysis will not disclose wider fields of application by recognition of hitherto unsuspected correlations with the principles of war. After preliminary definitions of war, the principles of war, geology and military geology, the development of military geology is outlined to show what aspects have been most useful and the phase of warfare to which they are best adapted. This reveals that there has been but little actual tactical application of geology in mobile warfare or a war of maneuver, and that its employment has not been worked out satisfactorily in the United States Army, although it has been developed to some extent by the Germans. Hence in our current engagements geology seems not to be utilized fully because of the erroneous belief that it cannot be applied with sufficient rapidity to keep pace with the course of modern combat. In order to bring the soldier and the geologist into mutual understanding, military and scientific thought are compared and shown to follow substantially the same outline. Then, terrain is considered from the viewpoint of army doctrine and geology, and emerges as the common denominator of geology and war. With terrain as the connecting link geology can be correlated with the principles of war. When military leaders are convinced that these correlations are valid and contribute to the strength of the principles of war, more widespread applications of geology to war will follow, and geology will rightfully take its place among the "front-line" sciences. Other conclusions are that, as the principles of war are immutable, and do not vary with change of weapons or tempo of combat, it follows that geology can keep pace with modern war in its most fluid tactical phases. Geology makes its chief contribution to war through the principles of Mass (Superiority) and Economy of Force, the fundamental law of war; but the principles of Movement (Mobility), Surprise, Security, and Simplicity are also strengthened through its application. The total effect of the application of geology to these

principles is superior information—upon which the possibility of success is principally dependent. Some suggestions are made regarding the geologic training and military qualifications of the modern military geologist. Finally, when all other things are equal, victory will come to him who makes best use of the ground.

INTRODUCTION

Wars have been waged since the beginning of human history—at least 3000 years—and probably they were carried on long before that, else the earliest warriors of whom we have record would not have been so accomplished. Indeed, if the origin of war could be traced it might be found to stem from the moment some misbegotten predatory ape found that it was easier to take something from one of his companions than to obtain the article by some more legitimate effort. Many wars have been fought since that day—and for many reasons. With the passage of time the numbers of men engaged have become larger, and tempo has increased with rapidity of movement and improvement of weapons and communications, until societies of nations have been included within the sphere of destruction. This modern war, or "total war" as it is called nowadays, recognizes no limitations of any kind whatsoever and is virtually a life and death struggle in which failure to secure ultimate victory means total, annihilating defeat. Conflicts of this nature involve the entire military, economic, social, and scientific fabric of the combatant nations. There can be no noncombatants. As the risk to national life became greater, proportionate demands were made upon the sciences to come to the aid of the societies that have nourished them. To their response is due in large part the increased tempo of modern war, and several of them, including chemistry, mathematics, and physics, have developed many truly front-line applications. Even warfare itself has developed a science. Nevertheless, in spite of the fact that the ultimate object of war today is to take and hold terrain, the contributions of the so-called group of earth sciences, with the exception of geophysics (Heiland, 1942), which presumably treat of this ground, have not been in proportion to its value or extent. This reluctance to make the fullest use possible of geology, geomorphology, and geography is by no means entirely due to the inability or unwillingness of the practitioners of these sciences. To some extent, of course, it results from unfamiliarity with military technique, with consequent uncertainty as to the field of application; and to some extent it is due to the soldiers' inadequate grasp of their scope or range of application. Fuller (1926, p. 187) has described the dependence of the soldier upon the peace-time effort of the scientist, saying: "In this study (of the theatre of war) the civil sciences can help us, and are progressively becoming, not mere handmaids of the soldier, but his closely collaborating partners. To render

this collaboration possible it is most necessary for the soldier to realize that, though he is the expert authority on the application of means, the scientist is the expert authority on their creation."

Insofar as geology alone is concerned, other reasons may be: suspicion of some of the fanciful speculations fostered by certain early workers in the field; that too much dependence is placed upon inductive or empirical methods; that most of the essential facts of geology are concealed from view; or, finally, because of undue emphasis on the historical aspect of geology. Naturally, the time sequence is one of the dominant ideas in geology, and it deals "so largely with past time that it is not popularly understood to include the present, but it certainly does include the present, and the future also, as fast as it arrives" (Davis, 1906, p. 497-498).

ACKNOWLEDGMENTS

Reading military history and science has been a hobby of the writer for many years, and ever since he became a professional geologist he has been interested in the application of geology to war. From time to time, usually under the stimulus of some article on military geology by a geologist not fully conversant with military science, or by a soldier with hardly more than a layman's concept of geology, he has been tempted to set down some of his own ideas on geology and war; but reasons for postponement of the necessary effort were always convenient, chiefly because of disinclination to make work of a hobby. The chance to combine both came with a detail to the Military Geology unit, U. S. Geological Survey, and particular thanks are due the Chief of the unit, W. H. Bradley, for continuous encouragement during the planning of this article and for the opportunity to complete it. Thanks are also due Major T. A. Holdahl, U. S. M. C., for his interest and for furnishing manuals on the Marine Corps doctrine on terrain.

DEFINITIONS

Numerous definitions of war are available, and their essential element is the exercise of violence or force. From the dawn of history to the beginnings of the twentieth century, warfare was regarded chiefly as an art, emerging from a handicraft or cruder sort of art. During the nineteenth century, military philosophers realized eventually that "every form of art can and should have its theory," and the theory of the art of war originated as these thinkers, among whom were Napoleon, Clausewitz, Jomini, and Dragomirow, sought to frame such abstract concepts or principles as would bring order and simplicity into an apparent chaos of historical observations on war. Naturally such investigations led to

some deliberation on a science of war, but Clausewitz (1940, Vol. I, p. 120), writing about 1827, finally concluded that "it is more fitting to say Art of War than Science of War." This view prevailed to about 1899 when Foch (1918, p. 12) cited approvingly the words of Dragomirow, a noted Russian general and military writer: "Nobody would think today of claiming that there can be a *science of war*. That would be as absurd as a science of poetry, of painting, of music." Nevertheless, a trend toward a science of war had been under way for some time, and Colonel Henderson (1905, p. 391), a brilliant English military critic, thought that it dated from the era of Napoleon. After World War I, Fuller (1926) approached the subject from a strictly scientific point of view and reviewed it thoroughly although tediously in his *Foundations of the science of war.*

Military men now recognize fully both an art and a science of war. The science of war is the study of military history with the object of determining whether any principles or all-pervading laws can be established, or whether there is really any "best way" of fighting. According to the doctrine of the United States Army [1] the principles of war are:

1. The Principle of the Objective.
2. The Principle of the Offensive.
3. The Principle of Mass (Superiority).
4. The Principle of Economy of Force.
5. The Principle of Movement (Mobility).
6. The Principle of Surprise.
7. The Principle of Security.
8. The Principle of Simplicity.
9. The Principle of Co-ordination (Co-operation).

These principles are fundamental and invariable. Although they all need not apply to any specific situation, they are not subject to exception, unless, perhaps, by a master of the art of war; and some military theorists might argue that no battle has ever been lost without one or more of them being violated. Their correct application enables the commander to deal properly with situations not previously experienced and constitutes the true measure of military art. They should be of noteworthy interest to those who are following closely the present operations in Africa, Asia, and Europe because their understanding affords a background for the appreciation of the daily military communiques and the too-often portentious announcements of the radio commentators. In this connection, however, it is well to bear in mind Fuller's (1926, p. 282) comment that "With a few elementary rules and a pinch of

[1] War Department, Training Regulations No. 10-5. Dec. 23, 1921.

military jargon any intelligent man can become what is called a 'strategist' or a 'tactician'."

The brief explanation of these principles that follows is from the doctrine of the General Service Schools, Fort Leavenworth, and is also available in Mitchell's *Outlines of the world's military history* (Appendix B, p. 740-741). The art of war consists of testing and applying these principles upon the field of battle. Their applications to the preparations for war and the direction of war is called strategy; their applications in specific battles and operations is called tactics.

1. *The principle of the objective.*—The purpose of a military operation is the attainment of the objective assigned a designated force. This objective constitutes the guide for the interpretation of orders, for the formulation of decisions, and for the empolyment of the means available. The nation, its military forces, and each element of the latter have their objective.

(a) The selection of national objectives depends on political, military, and economic conditions, which in every case will each vary in force and effect; but the following general rules apply:

(i) First, the neutralization or destruction of the power of the opposing military forces to give battle. This usually implies the defeat of the enemy's main forces as decisively as the means available will permit.

(ii) Second, the possession of localities which will attain the national objective, or contribute thereto.

(b) The objective assigned military forces must be in consonance with the national objective, and the objectives of each element of a military force must be contributory to the attainment of the objective of the force of which it forms a part.

2. *The principle of the offensive.*—Offensive action is the only means by which a decision is gained. When successful, the offensive brings victory, while the defensive can only avoid defeat. The only effective way to wage war is to act on the offensive for the purpose of delivering a main blow in the decisive direction. The offensive increases the effectiveness of a force adopting it, as it raises morale, permits concentration of effort, and allows freedom of action. The defensive should be assumed only to assist offensive action elsewhere, to gain time, or to utilize advantages of terrain, so as to compensate for weakness. Although the offensive confers great advantages, these advantages can be utilized only when the means available are sufficient to provide reasonable chances for success.

3. *The principle of mass.*—The term mass as used here means combat power. Numbers, weapons, tactical skill, fighting ability, resolution, discipline, morale, and leadership all contribute to this power. Success in war is attained by the employment of mass in a main effort at the proper time and place for the accomplishment of a definite purpose.

4. *The principle of economy of force.*—The application of the principle of economy of force is the means by which the mass to be employed in a main effort is obtained. The time and place of the main effort having been determined, men and means are conserved by reducing their employment in other directions to the minimum consistent with safety.

5. *The principle of movement.*—The term movement as here employed means the maneuver of combat elements.

In the offensive this principle is used to bring mass to close grips with the enemy in order to secure decisive results or to place it where it can attack with advantage.

In the defensive the principle is used to avoid or parry a hostile blow, or to place mass where it can counter-attack with advantage.

Movement is most effective when concealed. In many situations movement is made possible only by the effective employment of fire. In applying this principle, time, distance, and the means and power of movement must be considered.

6. *The principle of surprise.*—Surprise in some form is essential in order to obtain the maximum effect with the minimum loss. It may take the form of time, place, direction, force, tactics, or weapons. Secrecy, rapidity, and preparation are the main factors.

7. *The principle of security.*—Security embraces all measures taken to guard against observation and surprise, to insure against effective hostile interference with operations, and to gain and maintain the power of free action.

8. *The principle of simplicity.*—Simplicity is a relative term. As here used it means that military plans should be simple and should not provide for complicated movements, that orders should be direct and free from contingencies, that frequent changes of plan are to be avoided, and that unity of command is to be observed.

9. *The principle of cooperation.*—By cooperation is meant the working together towards the accomplishment of a common mission, of all military persons, i.e., "Team-work." Before it can be attained, thorough coordination must be secured. This principle applies to everything that is done in the military service. Cooperation within a command is attained when everyone interprets his instructions in an intelligent manner and executes them in accordance with their spirit and the intent of the authority issuing them. Between independent commanders, cooperation is attained by each working for the common good without reference to individual fortunes.

Numerous definitions of geology are also available, and their essential element is the earth. One of the more concise, minimizing the historical aspect, and thus appealing more to the engineer, is: "Geology treats of the energy and substance of the earth" (Van Hise, 1906, p. 526). Its principles are supposedly well known to geologists, who seek to apply them in their field work. Often this is a very difficult matter—so much so that some workers have questioned the existence of a science of geology. Some of its problems have taxed the abilities of several generations of geologists, and other fundamental problems are still in the realm of speculation. When considered from the standpoint of the exact sciences, "whose conclusions are capable of being, and for the most part are, established by experiment and verified prediction," it must be admitted that geology is not always an exact science.

Neither is war—the great variable here being the human element; and often the failure to evaluate it properly upsets every other calculation a commander may make.

Military geology may be defined simply enough as the application of geology to the art of war. Obviously, the application of one inexact science to another, or of one art to another, especially geology to war, is fraught with difficulties, not only because the place of direct application is the theatre of war or the battlefield, but because a facile application can be made only by one who has mastered the principles of each. As Clausewitz remarked many years ago, "combinations which are easily planned on paper can be executed only with great effort" (Clausewitz, 1942, p. 61).

The broad field of military geology may be subdivided naturally into three major branches:

Military geology
- A. Economic geology of war materials
- B. Geographic applications

C. Military engineering geology
   1. Base areas
   2. Zone of combat
      a. Stabilized front
      b. War of maneuver
         Tactical applications

The economic geology of ores, nonmetallic minerals, and fuels necessary to the conduct of war need not be considered here; but the relationships and ramifications of the subject are both numerous and complex (Smith, 1918, Pls. I, II). Exploratory programs are now being carried out by the Metals Section, Geologic and Alaskan Branches, U. S. Geological Survey, and by various sections of the U. S. Bureau of Mines; and the economic and production problems incident to mineral development are being handled by the War Production Board, Metals Reserve Corporation, Petroleum Administration for War, and other Federal agencies.

Geographic applications of military geology fall largely within the realm of strategy and logistics, or the disposition of armies preceding battle and their supply, and concern geology only to the extent that geology controls the major physical features of a region. They diminish, therefore, after the opposing forces are arrayed for battle and become subject to secondary features of terrain. Nevertheless, regional geographic control has been of great importance. It has been said that the collapse of the Moltke-Schlieffen plan for the invasion of France in August 1914 was due partly to the failure of the Germans to pay sufficient attention to the ground when the plan was drawn up; and the same criticism has been made of the French Plan XVII, which was prepared to halt the expected German drive (Duffer, 1932). In 1940 the Germans profited by their earlier mistake. With the rise of air transportation geographic control has been shaken, as in the recent New Guinea campaign, and it has never been as rigid and absolute as geographers would have us believe, for, as Rosinski (1943, p. 78-79) remarks, "no mere geographical feature possesses in itself intrinsic unchanging value, but gains whatever temporary value it may acquire only in the ever-changing web of the political situation and its military instruments." Even more forceful are the words of Foch (1918, p. 106) in comment on what he terms "senseless geography."

"An opening, a valley, are not particularly dangerous; there are roads outside the valleys, there are some on the highest plateaus, there are some wherever needed for commerce or the requirements of communication. The road in the valley or on the plateau is dangerous only by the use to which the enemy puts it. If the enemy does not use it, it has no tactical existence, and everything goes on as though it did not exist."

Applications of military engineering geology in Base areas are essentially those of peace-time civil engineering: water supply, heavy foundations, construction materials, and so on, with much greater emphasis on expediency. In making the distinction between geology behind a stabilized front and geology in a war of maneuver, it is well to remember that these situations are reversible, and that mobile warfare may change over into trench warfare in only a few hours, depending upon the ease of construction of field fortifications. Many other worthwhile suggestions have been listed recently by Price and Woodward (1942) and by Heald (1942) and are typical of the sort of thing the geologist thinks he could or should do if opportunity were provided; but, no matter how valuable these services at times might be, such articles seldom reach the military man, or carry conviction when they do, because they fail to correlate what seems to be obvious geologic applications with the principles of his profession and to help him to fight better and win battles.

DEVELOPMENT OF MILITARY GEOLOGY

Informal applications of natural philosophy to war have been made from the earliest times, long before the development of the science of geology, by an occasional soldier who possessed that intuitive knowledge of terrain known as "an eye for the ground." Herodotus (Book I, Par. 75), for example, tells how the Milesian philosopher Thales diverted the river Halys in 585 B. C. to permit the army of Croesus to cross in the absence of bridges; and he relates also (Book IV, Par. 200) of mining and counter-mining by the Persians at the siege of Barca, where there was an early application of military geophysics by a Barcean worker in brass. However, systematic attempts to apply geology to war did not come for centuries. Among the earliest of these efforts were those of the Bavarian engineer Von Gronner in 1826, and his lead was followed in Austria in 1855 by Baron Schmidburg, in England in 1862 by Captain Hutton, and in France in 1882 by Parandier (Draghiceanu, 1934, p. 5). Reference to geology and war was also made in 1868 by Major General Portlock in his small treatise on geology.

Throughout the long years of the American Civil War, although many officers on both sides were highly conscious of terrain, owing to previous service with the Corps of Topographical Engineers (Beers, 1942), little effort was made to apply any earth science to the conflict. Aside from Guyot's (1863) description of the southern Appalachian region for the use of the Northern army, the only known practical applications of geology were in the planning of the wing and crib dams built on the Red River just above Alexandria, La., to save Admiral Porter's gunboat

fleet trapped by falling waters during April 1864; and in the preparation of the Burnside mine under Elliott's salient at the siege of Petersburg, Va., June-July, 1864. Lieutenant-Colonel Joseph Bailey, Chief Engineer of the 19th Corps, then commanded by General W. B. Franklin, supervised construction of the Red River dams, April 30-May 8, after preliminary surveys of the rapids by Captain J. C. Palfrey, U. S. Engineers (Irwin, 1888, p. 358); and a mining engineer from Pennsylvania, Lieutenant-Colonel Henry Pleasants, suggested the location and supervised the coal miners of his regiment in driving the galleries of the Burnside mine (Powell, 1888, p. 548-549). Maps and cross sections illustrating the accounts of these operations indicate a thorough appreciation of the geologic conditions at each locality.

With the Confederate Army, according to Henderson (1905, p. 221), applications of the use of ground were much less advanced:

"Lack of reconnaissance was a fruitful source of indecisive successes and of unnecessary loss. Movements were projected and carried out without previous exploration of the ground or selection of the most effective line of advance. Little care was taken to discover the weak points of the enemy's position. The influence of topography upon tactics was unappreciated and the Confederate divisions attacked exactly where the adversary wished them to attack, instead of being directed by staff officers who, riding with the advanced scouts, had already made themselves acquainted with the ground, to the approaches most favorable to the assailant."

Evidence for the employment of geology in military operations during the Spanish-American war (1898) is not available, but shortly thereafter, during the Philippine insurrection, Dr. G. F. Becker, U. S. Geological Survey, made numerous impromptu applications (M., 1899), referred to in the following quotation:

"Dr. Becker early attached himself to the Bureau of Military Information of the Army, and soon became the right hand man of Major J. F. Bell, in charge. Official reports and papers that have since passed between Major Bell and the Commanding General, and letters from the officers to Director Wolcott, record numerous valuable services rendered by Dr. Becker to the army through the Bureau of Military Information, and also repeated acts of gallantry and soldierly usefulness in action, and accord him high praise for his conduct. He is repeatedly and strongly complimented by his military superiors, from Major Bell to Generals MacArthur and Otis. The reports, which cover events only to the middle of March, mention no fewer than 14 military reconnaissances and active engagements had with the forces, in all of which Dr. Becker took part."

Surely, these services entitle him to recognition as the first American military geologist. Unfortunately, Doctor Becker did not publish an account of his Philippine experience.

Other substantial advances were made during the Russo-Japanese war in 1906, when the Russians sought geologic advice in preparing heavy foundations of permanent fortifications (Kranz, 1934, p. 194-201); and the Japanese made a survey of the economic resources of Chosen (Korea). In subsequent years, Russian army engineer officers were required to

take courses in geology, hydrology, and geomorphology; but elsewhere interest was more or less dormant until just before World War I. For many years, however, elaborate studies in military geography with emphasis on empirical description of topography had been carried on by the French; and several extensive monographs on terrain by General Berthaut (1909-1910; 1912), published by the geographical service of the French Army, made notable contributions to geology. Unfortunately, in the war which came so soon, this service was unable to supply practical geological data for tactical needs, and the French general staff tried to obtain the necessary information from academic geological sources, but it could not be applied immediately or effectively (Draghiceanu, 1934, p. 6).

In Germany, in the meantime, the few studies that were being made laid stress upon geologic rather than geographic applications of geoscience to war. As early as 1913, Dr. Major Walter Kranz, then a captain in the corps of fortification engineers of the German Army, and later Director of the Geological Survey of Wurtemburg, had arranged special courses in military geology for other engineer officers and published a short article calling attention to the use of geology in war. Draghiceanu (1934, p. 5) implies that Kranz's influence inspired the speech by the Minister of War, Von Falkenhayn, before the Reichstag in 1913, requesting the organization of a geologic service with each army corps; and he credits Kranz with being the "real originator" of German military geology. However, not much seems to have been done until after the organization of the geologic staff of the British Army in 1915; even as late as 1916, newspaper articles deplored the lack of organization in the geological work of the German Army. In general, the work of the British geologists excelled that of the Germans. Spurred on to greater efforts, the Germans are said to have made professional use of 250 geologists during the last year of the war, and about 100 of them are thought to have been employed on the Western Front. Additional details of the organization of the German geologic staff in World War I, as well as that of the British and American Armies, have been given by Lieut.-Col. A. H. Brooks (1920b, p. 93-96), Chief Geologist, American Expeditionary Force, in his professional paper on *The use of geology on the Western Front*. Particular emphasis has been placed upon the development of German military geology because of their sustained interest in this field in the years following the war, which resulted in a marked increase in excellent technical literature on the subject, coinciding, fortuitously perhaps, with the rise of the Nazi Party in 1933 and the subsequent rearming of Germany.

Turning again to the United States; within a few weeks of the declaration of war, April 7, 1917, the first semi-official American publication on the application of geology to war, *What a geologist can do in war,* was written by R. A. F. Penrose, Jr. (1917), under the auspices of the Division of Geology and Geography, National Research Council, but attracted so little attention that it was soon forgotten. Some months later, a somewhat more comprehensive textbook, *Military geology and topography,* appeared under the same auspices (Gregory, 1918). Although the chapters on Land Forms and Map Reading and Map Interpretation are as good as any that appeared up to that time, it contains little of interest to an experienced geologist and nothing of real appeal to a professional military man, fully justifying the naive remark in the preface that "the relation of geology to military activities is unfamiliar to American students." In spite of this inadequate background, following the example set by the British Army, the geologic section of the American Expeditionary Force was established promptly as part of the office of the Chief of Engineers in September 1917, with Lieut.-Col. A. H. Brooks of the U. S. Geological Survey in charge (Brooks, 1920b, p. 94). Authorization had been obtained for the assignment of five geologists to each Army, or one for each Corps, but the armistice was signed before complete organization had been accomplished and before much practical work could be done.

Field operations of the geologic staffs of the American, British, and German armies were conditioned largely by the more or less stabilized character of trench warfare on the Western Front and consisted chiefly of investigations contributory to such essential military engineering functions as water supply, field works, mining, and countermining. All these applications are covered thoroughly in the comparative flood of technical literature on the subject during and after the War (Table 1, 1915-1920), and seem to have fixed the pattern for the military use of geology in the minds of many high-ranking officers as well as interested geologists, because in mobile warfare the importance of more or less permanent fortifications and engineering works, except in base areas, is reduced in proportion to the extent of the probable area of combat. During the next period, 1921-1925, the literature is notable chiefly for the German series on *Die Kriegsschauplatze* (Wilser, 1926-1929) and Villate's (1925) important work on military geography in the French Army. The consensus of military engineering opinion is that geology did make worthwhile contributions to the conduct of the war. However, with the exception of Villate's book, the literature of these periods contains very little reference to the employment of geology in mobile warfare; and, inasmuch as for many years military thought suffered from a "defense complex," with its implica-

tion that future land warfare would partake of the nature of a siege, progress in the application of geology to mobile type of warfare suffered accordingly.

With the widespread relaxation of military thought and effort after World War I, interest in the use of geology even in stabilized fronts waned and all but died out, except in Germany. The following summary of literature on military geology illustrates the trend in emphatic manner. Table 1 is based largely upon a recent bibliography (Bucher, 1941; Siegrist and Platt, 1943), admittedly incomplete, but listing a sufficient number of titles to give some foundation for analysis. Were more to be considered, the additions would probably be first to the German list and second to the others (Roumanian, Russian, Swiss, and so on) with little or no change in the position shown. Only papers referring directly to some phase of military geology are included; titles with indirect bearing, such as those on aerial photography, geography, mapping, military sketching, and topography, are omitted.

TABLE 1.—*Analysis of literature on military geology*

Origin and Frequency of Titles

Period	United States	British Empire	France	Germany	Other
1910-1914	0	1	3	2	0
1915-1920	26	4	1	28	0
1921-1925	0	1	2	9	0
1926-1930	0	0	0	9	0
1931-1935	2	0	0	10	4
1936-1942	10	2	2	20*	5

* German literature up to 1939 only.

Two things are very apparent: the persistence of German interest in military geology, and the sharp increase in the number of titles immediately preceding the outbreak of World War II in September 1939. Examination of the contents of the literature for this period is likewise revealing. Chiefly noticeable are the appearance of articles of book length —practical handbooks (Wasmund, 1937; Von Bülow *et al.*, 1938) on military engineering geology, the evidence of sound military collaboration, and an increasing awareness of the possibilities of using geology in a war of maneuver. Obviously the Germans recognized some geologic application that would promote the conduct of the war they were planning so carefully.

Risk is one of the immutable characteristics of war—risk of defeat, of everything life holds dear, of life itself. It cannot be eliminated, something must be left to chance; but it can be reduced, and the good general senses when it is at a minimum and then moves forward. If the interpre-

tation of a geologic map with a topographic base as outlined by Sonne (1936, p. 192-195) suggests anything at all, it is that by means of a systematic analysis an improved form of terrain appreciation can be developed which goes far in reducing risks of ground by virtue of its ability to forecast the form and substance of terrain under almost any condition of weather and climate. Information of this type must have been found to be a prerequisite for the planning and conduct of the blitzkrieg, and its value to a commander in an encounter battle is priceless. In the light of the recent British success in North Africa, it is pertinent to quote some earlier remarks on terrain in this type of war by the commander of the VIII Army. Writing in 1937, General B. L. Montgomery said:

"So important is ground, and so great can be the dislocation caused by obstacles and demolitions, that the initial encounters between two forces are likely to develop into endeavors to secure such ground as will enable the subsequent battle to be staged successfully. Failure to secure this ground may have far-reaching results, both tactically and administratively. Obviously, then, success in these initial encounters will be the aim of every commander and he will have to consider most carefully the best dispositions for his force in order to insure this initial success. In thinking out the problem it must be remembered that a wholly mechanized unit or subunit is easily held up by obstacles covered by A. T. weapons, and that in order to defeat these tactics it will be necessary to have immediately available subunits that can operate on foot across country, using covered approaches and outflanking the resistance. Bridges, defiles, M. T. turning-points, road communication centres—all these have now assumed an importance they never possessed before, and a commander will aim at securing such places as his forward move progresses" (p. 341-342).

However, another British officer, Colonel (now Major-General, retired) J. F. C. Fuller (1926, p. 262) made perhaps the first approach to indicating the desirability of modern forecasts of terrain conditions in the following words:

". . . there are many conditions which we can know—such as the nature of the theatre of war; the system of communications traversing it; the fortresses securing these communications; the commercial and industrial centres; and a host of other factors. From these we can plan out a strategical and tactical map on the lines of a geological chart, and from this map we can learn the possible and then the probable movements of the enemy."

Two years later, in writing on the future of military engineering, Fuller (1928, p. 26-27) elaborated upon this idea, and his words are quoted at some length:

"Today (1928), land strategy is almost entirely woven on roads and railways, but cross country machines, though they will not abolish roads and railways, will give to strategy another dimension. Armies will be able to move as organized units where they never moved as such before, and this increase in strategical power will radically change present day tactics. Heretofore, great battles have generally been fought in the close vicinity of strategical avenues of approach; so much so has this been the case that it was often possible to predict where they would take place. But if these lines of approach widen in all directions, battles may take place anywhere in an extended and extensive area. The old conception of fronts may vanish altogether; fronts may be anywhere."

In other words, General Fuller foresaw the release of strategy from geographic control.

He continued:

"The means whereby the engineer can supply information to the army must remain surveying and map-making. Mapping has now been reduced to so fine an art that on first thoughts it may seem there is little room for improvement. This would be a correct deduction if the armies of the future were to be similarly organized to those of today. But this is not going to be the case, consequently what I will call 'roadless' strategy and 'area' tactics will demand a different type of map. To know where roads, railways and rivers run, where cities, villages, mountains and forests are situated will not be enough. All these common geographical features will be useful, but besides them must be added a host of strategical, tactical and administrative 'features'. For example, ground will have to be colored to show where tanks and roadless vehicles can move at ease, can move with difficulty, and cannot move at all, so that at a glance a commander is able to see from his map how best to deploy his mechanized arms. . . .

"In brief, the surveyor and map maker must more and more turn from purely civil map requirements to future strategical, tactical and administrative military requirements, on the accurate knowledge of which the movement and supply of armies will depend. Here is opened up to us a completely new theory of military cartography, and its development is essentially one of the duties of the engineer. The side which possesses the best maps will strategically move the quicker, and tactically commit fewer blunders. Consequently, the better these maps are, the more will the engineer be able to assist the Army, and to the detriment of the enemy should he be less well provided."

The "new theory of military cartography" opened up here is essentially that devised by Sonne (1936) several years later, and now followed with improvement by the Military Geology unit, U. S. Geological Survey, in preparing terrain appreciation folios for the Intelligence Branch of the Corps of Engineers.

COMPARISON OF MILITARY AND SCIENTIFIC THOUGHT

One of the essential elements of military education is training in correct procedures of thought, so that, no matter how turbulent or confused local circumstances are, sound conclusions may be drawn from whatever information is available. Officers of the armed forces of the United States, and of other nations as well, are instructed in the use of a rather definite procedure, which has but one purpose—to evolve a plan or reach a decision. The moral courage necessary for the execution of the plan falls under the heading of Leadership and is of no concern here. The outline followed is called an "Estimate of the Situation" (War Department, 1940b; Marine Corps Schools, 1937; Muller, 1940). That given below is highly skeletonized, but the major headings are more or less common to all forms of the estimate. Opposed to it is the standard procedure of scientific method or thought as used by the geologist. Facts are collected through field observation, and inductive methods of reasoning are used to develop a hypothesis; then its consequences are tested by deductive inferences and further observation. The comparison that follows has been adapted, with some

modification in order to follow our own form of estimate more closely, from that made recently by Captain A. S. Wilson (1937), Australian Staff Corps.

Military Estimate of the Situation	*Outline of Scientific Method*
1. The Mission. (The Tactical Situation)	1. The Problem.
2. Opposing Forces. Enemy forces. Our own forces.	2. Known facts, and assumed factors.
3. Possible Lines of Action. Open to the enemy. Open to our forces.	3. Possible hypotheses.
4. Determination of our best course of action. a. Analysis and comparison of suitable courses of action (Deductive inferences from the course adopted). b. Final evaluation of commander's course of action (Testing against experience, doctrine or principles of war.)	4. The selected hypothesis. a. Deductive inference from the hypothesis. b. Testing the deductions by observations and experiment.
5. The Decision or Plan.	5. Development of the hypothesis.

No essential difference exists. This should be reassuring to the soldier intending to apply any science to war, because, even if he and the practicing scientist do not have a common technical vocabulary, the fact that the thought process is the same will give him confidence in the scientist's conclusions; particularly so as the latter, like the soldier, is compelled to work with fragmentary and sometimes inaccurate information.

TERRAIN

Under the heading 2, Opposing Forces, in this Estimate of the Situation are usually listed many technical factors or elements conditioning local circumstances that may affect either the enemy or our own capabilities to act. Naturally, only those that apply are considered, and part of the art of war is to recognize those that are relevant; but certain of them such as Time and Space and Terrain are always present, and sometimes are common to both sides. These factors are generally inseparable, for Time and Space may limit or define the Terrain to be considered. The definition of terrain in the United States Army (War Department, 1940, p. 6-21) is:

> "Terrain is an area of ground considered as to its extent and topography in relation to its use for a particular military operation. From either direct observation or study of maps and aerial photographs the eye gets a picture of the ground with its drainage systems, commanding elevations, wooded and open areas, and works of man. Terrain appreciation is the evaluation of this picture to determine effect of the terrain on lines of action open to opposing forces in the area.
>
> "By reason of his specialized training the unit engineer is the terrain specialist on the unit commander's staff. As such he must understand effect of terrain upon military operations and must be prepared to make recommendations thereon at all times, particularly in defensive operations. . . .

"Terrain is always evaluated in terms of five factors: observation, fields of fire, cover and concealment, obstacles, and communications."

Military literature of all ages, from Sun Tzu (500 B. C.) to Foertsch (1940), is replete with references to terrain, or "ground," or "country" (they all mean the same), and they convey such a definite picture to the soldier that he seldom bothers to define it. That it includes the natural and artificial or cultural features of the ground is well understood; but whether, excluding surface relief, it possesses a third dimension or depth into the earth has caused uncertainty among some geologists. The generality of the official definition given above may be interpreted as including the depth to which the heaviest artillery projectiles and aerial bombs may penetrate (War Department, 1940a, Table VI, p. 48; Table X, p. 54-55; Table XI, p. 56; Table XII, p. 56) and, further, the additional depth or cover necessary to secure protection from them (War Department, 1940a, Table XXVI, p. 214). The figures given allow a maximum depth of about 50 feet, and mining operations may involve work under considerably greater cover. Thus the geologist need have no fear that he is encroaching upon the terrain of the soldier if he insists that in addition to natural and cultural features it also include surficial and subsurface features. Here, then, in terrain, is the common meeting place of the soldier, the geographer, and the geologist.

The soldier's interest, of course, is purely utilitarian and objective; he "must make ground serve his purpose and never subordinate his initiative and will to limitations of terrain. Ground is only a *means* to the attainment of his objective, which is the enemy himself" (Muller, 1940, p. 14). There was a time, however, as Clausewitz (1940, vol. II, p. 238) pointed out, when generals debated whether "The battalion defended the mountain or the mountain defended the battalion." An example is cited by Foch (1918, p. 29):

"At that time, war consisted of maneuvers, of positions. And so we see him (Henry of Prussia) making in 1806 the most unfortunate plans; trusting in particular the safety of the Prussian army to the position at Ettersberg near Weimar, exhorting the fleeing remnants from Jena to run there, as if the mountain alone without a strong army could in some way stop the victorious flow of the French."

The geographer, insofar as he is concerned with geomorphology, is interested chiefly in the description of the natural landscape and classification and labeling of land forms. The geologic foundation of geomorphology was pointed out many years ago by Albrecht Penck (1906, p. 613), the noted German geographer.

The geologist's interests, however, not only cover these aspects of terrain, but go beyond. In the first place, the word also exists in his technical vocabulary, sometimes spelled "terrane", and is defined as a geologic formation (a mappable rock unit), or a group of formations, but

usually as the area of surface over which a particular rock or group of rocks is prevalent.

Land forms also intrigue the geologist because they result from the operation and interaction of geologic processes—weathering, erosion, transportation—upon geologic materials—rocks. His concern is not only with their substance but with their form as well, because, as Cotton (1942, Preface) has remarked, they give "access to a record—which is in many cases the only record available—of a late period in (geologic) history very scantily documented by stratigraphy." He also knows that "Topographic features are not unrelated individuals with haphazard forms and positions. They have been developed by geologic processes in an orderly fashion and to a large extent reveal their origin and history" (Gregory, 1918, p. 162). This concept of a regular sequence of forms is embodied in the geologic principle of the physiographic cycle and has a bearing on several of the principles of war through terrain. When applied properly it forms the basis of forecasting terrain conditions and so gives to the geologist, more than to any other man, that easy understanding—sometimes it is not so easy—or appreciation of land forms which is such an essential element of "an eye for the ground." This has been called an "instinctive eye for configuration, the judgment of how distant ground, seen or unseen, is likely to lie when you come to it" (Amery, 1931, p. 53). All the great captains have had it: Alexander, Hannibal, Caesar, Marlborough, Frederick, Napoleon, Lee, Sherman. They knew what Colonel Muller (1940, p. 123) has recently said so well, "The entire struggle between attacker and defender . . . hinges upon making correct use of terrain, and this depends upon interpreting ground forms, making best use of the ground despite its deficiencies, in short, having an 'eye for terrain' ".

With these men, however, an "eye for terrain" was not just a vague intuition, but the combined result of close personal observation, careful analysis of intelligence reports, and clear reasoning. In other circumstances and times they might have become outstanding geologists and geomorphologists. Their method was common to all and has been described by Henderson (1905, p. 80):

"If we look back on history, we cannot but be struck by the exceedingly important part that the appreciation or neglect of the capacities of ground has played in every campaign. The most brilliant victories have been won by maneuvers which, if not suggested by the physical features of the battlefield, were at least deprived, by the nature of the ground, of half their risk. Rosbach, Leuthen, Austerlitz, Friedland, Dresden, Vittoria, Orthez, Chancellorsville, the Green Hills of Plevna, are examples. Nor can we fail to notice that the object of the great masters of tactics in carefully reconnoitering the enemy was to discover the key point or points of his position, and to judge for themselves how each separate locality, wood, village, farm, or hill, might be turned to account and fitted into the plan of battle. In short, we see in many most successful battles an almost methodical progression

from point to point, each successive capture weakening the enemy's position and paving the way for a further and more decisive advance; and the method pursued seems to have been in every case the same. 'By threatening the village on the left, seizing the wood in the rear of it, I shall attack the hill on his right, and having captured this, bring every available gun to bear upon the central ridge, and attack, under cover of their fire, in full strength.' This, or something very like it, appears to have been the ordinary mental process of such leaders as Frederick, Wellington, Napoleon, and Lee, and in many respects it is still eminently adapted to the field of battle."

How much more complete this analysis would be with some application of geology! Then the estimate in part might read, "—I shall attack the hill on his right where the fragmentation effect of our fire will be great and he cannot be heavily entrenched owing to the hardness of the rock," and so on.

CORRELATION OF TERRAIN WITH THE PRINCIPLES OF WAR[2]

The close and mutual associations of geology and terrain are indisputable. Is there any correlation between terrain and the principles of war? If these principles still hold in this day of the *blitzkrieg*, if their correlation with the terrain over which the "blitz" moves is sound, and if our correlation of geology and terrain is valid, we may have the answer for those sceptical generals and timid geologists who doubt that modern geology can keep pace with modern war.

In correlating terrain with the principles of war only those elements of the principles that have a bearing on terrain will be emphasized. Nevertheless, consideration even from this limited point of view illustrates their singular unity, for the thread of terrain links them all together.

Ordinarily, the tactical principle, "utilization of the terrain," is embodied in the third principle of war, Mass (Superiority). Among its distinctive elements developed by efficient use of terrain are the five familiar factors of terrain evaluation: observation, fields of fire, cover and concealment, and communications. Others are position, central lines, command, decisive direction, or any other element of ground that will contribute to combat power.

Terrain is utilized in the Objective (1) by assisting in the determination and maintenance of decisive direction. Great confusion has resulted from loss of direction on the battlefield, collision of friendly units or deviation from the Objective sometimes resulting. In addition to the use of maps and compass, much dependence is placed upon direction lines or boundaries based upon easily recognized topographic features. These boundaries, of course, do not control the maneuver, but they must conform to it. The Objective may also be defined in terms of terrain; but

[2] Par. 3, p. 2-3, of manual on terrain (Marine Corps Schools, 1936) has been drawn upon freely in the preparation of this section, and unassigned quotations have been taken from it.

many times a unit overruns its objective or is stopped short of it because of failure to recognize the features of the ground. At their best, many boundaries and terrain objectives are indefinite; conspicuous landmarks change in appearance when viewed from different directions; maps may embody deceptive errors whose correction requires calm study; visibility may be poor owing to darkness, fog, dust, smoke; and above all, orientation may be lost owing to shock of fire or combat. In World War I the matter of correct identification of the terrain was considered so essential that, before some large offensives, "a large-scale relief model of the battle area was constructed, and officers rehearsed the coming attack while studying this miniature representation of every hill, valley, knoll and ravine which they would have to cross (Johnson, 1920, p. 182). The French Service Géographique de l'Armee became so proficient in the preparation of these models that they could be supplied upon 24 hours' notice.

The principle of the Offensive (2) is also favored by taking greatest advantage of the terrain. Factors favoring the offensive are good frontal observation, compartments and corridors leading into the hostile position, few corridors leading from the enemy's position, ground favorable for tank action, open terrain favoring maneuver, fields of fire and centralization of command, obstacles on the flanks and protected routes of communications.

Any area having terrain features on opposite sides that restrict observation and prevent flanking fire by direct laying from an adjacent area is called a compartment of terrain. These features are an arbitrary fundamental unit of convenience in military classification of terrain. Their size is widely variable depending upon the distance to the horizon from an observer in the compartment. It is essential to note that the controlling element in their delineation is not topography but direction of movement of the forces operating therein. Thus, if a compartment is elongated in the direction of movement it is called a terrain corridor. If the long dimension lies across the axis of movement, it is called a cross compartment. There may also be oblique compartments (War Department, 1940a, Par. 10, p. 8-12).

The principle of Economy of Force (4) is considered by some military writers (Fuller, 1928, p. 201) to be the fundamental or controlling law of war. Advance information as to the form and substance of the terrain may result in great Economy of Force. The land forms determine the naturally strong points or sectors that can be manned lightly, and the threatening approaches where corridors lead into a defensive position that must be manned more heavily. Sectors for the main effort and secondary or holding attacks in offense are likewise suggested. A good example of the application of the principle of economy of force in the choice of

a defensive position is Lee's selection of the final Confederate position at Cold Harbor, Virginia, in June 1864 (Freeman, 1935, p. 437). The lithology of the ground determines where rapid and easy excavation is possible, and where field works can be prepared only with great expenditure of effort, where fragmentation effect is high, subsurface drainage poor, and so on. All these factors may save time, effort, movement, and life. When areas of unfavorable ground are known, the enemy may be maneuvered into them in order that his effort may be more wasteful and thus drain his strength and slow him down.

In this connection, however, Clausewitz's (1942, p. 43) warning should ever be in mind:

> *"Never to depend completely on the strength of the terrain and consequently never to be enticed into passive defense by a strong terrain.* For if the terrain is really so strong that the aggressor cannot possibly expel us, he will turn it, which is always possible, and thus render the strongest terrain useless."

Joseph E. Johnston (1888, p. 262), whose flank was turned numerous times by Sherman as he fell back on Atlanta, expressed the same thought in these words:

> "Mr. Davis descants on the advantages I had in mountains, ravines, and streams, and General Sherman claims that those features of the country were equal to the numerical difference between our forces. I would gladly have given all the mountains, ravines, rivers and woods of Georgia for such a supply of artillery ammunition, proportionally, as he had."

Johnston, it will be recalled, was a former member of the Corps of Topographical Engineers and a master in the use of ground; Sherman thought Johnston equalled Lee in all the elements of generalship. Another example from the American Civil War is the by-passing of the Confederate position on the North Anna River, Virginia, by General Grant, May 24, 1864 (Freeman, p. 357 (map), 435); and many others could be cited from the present war, one of the most interesting being that of Dakar on the coast of French West Africa, which soon fell of its own weight like a ripe apple.

The principle of Movement (5) is associated with the selection of routes that avoid obstacles, both tactical and protective. They may be of many kinds, and include such land forms as hills, ridges, or steep slopes in general, boulder-strewn slopes, woods, swamps, lakes and rivers, and gumbo or clayey soil that may be impassable when wet and plastic and tenacious when drying out. Bentonitic shale, such as is so widespread on the Cretaceous terrain of the Rocky Mourtain States, may suddenly become a formidable barrier under the influence of a passing shower. Rapidity of modern movement requires that the location and extent of these obstacles be known in advance. Here again the essential knowledge involves more than classification of land forms, for the proper selection of route also

demands selection of the route of greatest velocity. This element, when combined with Mass, develops momentum, which upon impact with a hostile force is released as shock; and shock is usually associated with Surprise. In country of low relief the lithology of the surface exerts greater control upon speed of movement than do the land forms. Efficient movement or mobility also depends upon the recognition and use of interior lines, the use of covered routes of approach, and "the selection of ground which permits the maximum use of fire power developed by the characteristics of modern weapons."

Surprise (6) is one of the fine arts of war and "still the most deadly of all weapons." One must assume that the enemy "will devote the whole force of his intellect to the problem of bringing it about" (Henderson, 1905, p. 56). Increased facilities for observation, mobility, and communications militate against it when combined with vigilance. Nevertheless, our most serious military disasters have been obtained through our being surprised. In land warfare the terrain factors that contribute to surprise are increased or unsuspected efficiency of Movement, use of unknown or covered approaches, routes of unlikely approach, defiladed assembly areas, favorable lines of departure, and the offensive features of the ground.

The essential element of Security (7) is vigilance. This is strengthened by the use of natural and artificial obstacles on the front and flanks, and cover from fire and observation. In the absence of complete information of the enemy, a thorough analysis of all terrain factors—topography, cover and concealment, ground characteristics, water conditions, and so on—is necessary to deduce his most probable dispositions, rate of movement, and the direction from which he may be expected to appear.

Simplicity (8) is favored by thorough regional knowledge of the terrain, by designating boundaries and objectives that are easily recognized and assist in maintenance of the decisive direction, and "finally by directing simple maneuvers which conform to the mission assigned and are naturally adapted to the terrain."

Lastly, Cooperation or "Coordination (9) of effort is secured by assigning terrain objectives and tasks that provide mutually supporting operations," or allow unity of action.

RELATION OF GEOLOGY TO THE PRINCIPLES OF WAR

Brief as this outline of the chief relationships between terrain and the principles of war may be, it is evident that every principle is associated with one or more aspects of terrain, which provides the link with geology. Terrain is the common denominator of geology and war. Some of the principles exhibit closer relationships than others, and these appear to

be Mass (3), Economy of Force (4), Movement (5), Surprise (6), Security (7), and Simplicity (8).

Should any doubt remain as to the geologic control of terrain, all that is required for demonstration is a terrain map on which ground areas with similar characteristics are shown by identical patterns. When this is superimposed upon a geologic map of the same region the areas of similar terrain usually will coincide closely with districts in which the geologic factors (stratigraphy or lithology, structure and physiographic stage), the hypsometric factor of altitude, and the meteorologic factor of climate are essentially equal.

The most necessary requirement of the military geologist is a good geologic map. Speaking shortly after the last war to the Geological Society of Washington, Col. A. H. Brooks (1920a), the former chief geologist of the A. E. F., said: "Should warfare continue to develop on the scale and with the scientific refinement witnessed by the last five years, geologic maps will in time be considered almost as essential to offensive and defensive operations as are topographic maps."

With such a map in hand, observing physiographic stage as he proceeds, no matter what the rate, slogging along with the infantry, racing across the country with the armored force, or flying over it with the air force, the military geologist has "an eye for the ground"; indeed, he has more than that—he has insight into the ground. His mind can always be ahead, evaluating, appreciating, and forecasting every military feature of the terrain as it approaches and flows past.

QUALIFICATIONS OF THE MILITARY GEOLOGIST

What sort of man should this military geologist be?

In the first place, he should be a professional geologist of the widest range of sound training and field experience in areal mapping, engineering geology, geomorphology, and the geology of unconsolidated materials. Particularly desirable are the qualifications of the engineering geologist, as outlined by Berkey (1929, p. 5). "He must have the principles of geology so well in hand and feel so sure of them in their application to the actual ground as it is that he is not in the least disturbed at finding everything of a geologic nature belonging to a particular project materially different from anything he has ever seen." Text books and field manuals are of small value; once in the theatre of war it is too late for grounding in either theoretical geology or the theory of war. As Muller has said of the commander, "He must meet every new situation with an open mind, recognize novel and unprecedented conditions, and apply both knowledge and imagination with a deft touch" (Muller, 1940, p. 7).

Secondly, he must be a soldier with qualifications that fit him for the Corps of Engineers. In addition to the basic training he should have an additional background of staff training and experience, for his function will be chiefly advisory and reconnaissance; but he must be able to fight and lead troops if through the fortune of war command should descend to him. However, his knowledge of military history, strategy, tactics, and technique of modern arms should be developed not so much for the purpose of command as for an analytical tool for evaluating the military features of the terrain. He should be able to appreciate the military situation so that his work can be properly subordinated and correlated to the mission of the force to which he is attached. He should "know accurately and in detail what troops can and cannot do" so that impracticable and infeasible suggestions may be avoided; and he should be able "to foresee what the troops will be able and will not be able to do in the future" (Fuller, 1928, p. 24) so there will be no lapse in the continuity of his work. And he will ever bear in mind that the contributions he makes to terrain appreciation are only an aid to the attainment of the real objective, which is the enemy himself.

SUMMARY AND CONCLUSIONS

(1) Geology can be correlated with the principles of war through terrain.

(2) As these principles are immutable, and do not vary with change of weapons or tempo of combat, it follows that geology can keep pace with modern war in its most fluid tactical phases.

(3) Geology makes its chief contribution to war through the principles of Mass and Economy of Force, the fundamental law of war; but the principles of Movement (Mobility), Surprise, Security, and Simplicity are also strengthened through its application.

(4) The total effect of the application of geology to these principles is superior information—upon which the possibility of success is principally dependent.

(5) When all other things are equal, when the die is cast upon some fire-swept field, victory will come to him who makes best use of the ground and, like Antaeus of old, takes new strength from the earth.

REFERENCES CITED

Amery, L. S. (1931) *Mountaineering as training for war,* Royal Eng. Jour., vol. 45, p. 53.

Beers, H. P. (1942) *A history of the U. S. Topographical Engineers, 1813-1863,* Military Eng., vol. 34, pt. I, no. 200, p. 287-291; pt. II, no. 201, p. 348-352.

Berkey, C. P. (1929) Responsibilities of the geologist in engineering projects, In *Geology and engineering for dams and reservoirs,* Am. Inst. Min. Metall. Eng., Tech. Pub. no. 215, p. 4-9.

Berthaut, General (1909-1910) *Topologie étude du térrain,* Imprimiere du service Géographique de l'armee, Tome I; Tome II, 1910.

——— (1912) *Connaisance du térrain et lecture des cartes (Etudes topologiques),* Imprimiere du service Géographique de l'armee.

Brooks, A. H. (1920a) *Application of geology to war,* Washington Acad. Sci., Jour., vol. 10, p. 331-333.

——— (1920b) *The use of geology on the Western Front,* U. S. Geol. Survey, Prof. Paper 128-D, p. 85-124.

Bucher, W. H. (1941) *Bibliography of military geology and geography,* Geol. Soc. Am., New York.

Clausewitz, General Carl von (1940) *On war* (Translated by Col. J. J. Graham), 3 vols., Kegan Paul, London, 4th printing.

——— (1942) *Principles of war* (Translated by H. W. Gatzke), Military Service Pub. Co., Harrisburg, Pa.

Cotton, C. A. (1942) *Geomorphology—an introduction to the study of land forms,* 3d ed., Melbourne.

Davis, W. M. (1906) *The relations of the earth-sciences in view of their progress in the nineteenth century,* Inter. Cong. Arts Sci., vol. IV, p. 497-498, New York.

Draghiceanu, M. M. (1934) *Geologie de Rasboi,* Revista Geniuliu, Nov.-Dec. (Geology of war. Radio lecture delivered in July 1933.)

Duffer, Général (1932) *L'élément terrain en stratégie,* Révue Militaire Française, April-July.

Foch, General Ferdinand (1918) *The principles of war* (Translated by J. de Morini), H. K. Fly, New York.

Foertsch, Col. Herman (1940) *The art of modern warfare* (Translated by T. W. Knouth), Oskar Piest, New York.

Freeman, D. S. (1935) R. E. Lee, vol. III.

Fuller, Col. J. F. C. (1926) *The foundations of the science of war,* Hutchinson and Co., Ltd., London.

——— (1928) *Scientific soldiership,* Royal Eng. Jour., vol. 42, p. 201.

——— (1928) *The future of military engineering,* Royal Eng. Jour., vol. 42, p. 24, 26-27.

Gregory, H. E. (1918) *Military geology and topography—a presentation of certain phases of geology, geography, and topography for military purposes,* Nat. Res. Council, Div. Geol. Geog., Yale Univ. Press.

Guyot, Arnold (1863) *Notes on the geography of the mountain district of western North Carolina* (manuscript), Princeton, N. J. Copy in library of U. S. Geol. Survey. Cited by Brooks, A. H. (1920b, p. 89).

Heald, K. C. (1942) *The rhyming letters for victory,* Assoc. Am. State Geol., Jour., vol. 13, no. 4 (mimeographed); Am. Assoc. Petrol. Geol., Bull., vol. 26, p. 1838-1842.

Heiland, C. A. (1942) *Geophysics in war,* Colo. School Mines Quart., vol. 37, no. 1.

Henderson, G. F. R. (1905) *The science of war,* Longmans Green, London.

Herodotus: *Book I, Clio; Book IV, Melpomene* (Translated by Geo. Rawlinson).

Irwin, R. B. (1888) *The Red River campaign,* Battles and Leaders of the Civil War. vol. IV, 2d ed.

Johnson, D. W. (1920) *Contributions of geography,* In *New world of science, its development during the war,* New York.

Johnston, Gen. J. E. (1888) *Opposing Sherman's advance to Atlanta,* Battles and Leaders of the Civil War, vol. IV, 2d ed.

Kranz, Walter (1913) *Militargeologie,* Kriegstech. Zeitschr. Officiere aller Waffen., Bd. 16, p. 464-471.

—— (1934) *Beiträge zur Entwicklung der kriegsgeologie; III. Russland,* Geol. Rundschau, Bd. 25, p. 194-201.

M., W. F. (1899) *Geological expedition of Dr. Becker to the Philippines,* Science, n. s., vol. IX, p. 722-723.

Marine Corps Schools (1936) *Terrain,* Quantico, Virginia.

—— (1937) *Estimate of the situation and operation plans and orders,* p. 4-15, Quantico, Virginia.

Mitchell, Brig. Gen. W. A. (1940) *Outlines of the world's military history,* 4th ed., Military Service Pub. Co., Harrisburg, Pa.

Montgomery, Brig B. L. (1937) *The problem of the encounter battle as affected by modern British war establishments,* Royal Eng. Jour., vol. 51, p. 341-342.

Muller, Col. H. LeR. (1940) *Technique of modern arms,* Military Service Pub Co., Harrisburg, Pa.

Penck, Albrecht (1906) *The relations of physiography to the other sciences,* Inter. Cong. Arts Sci., vol. IV, p. 613, New York.

Penrose, R. A. F., Jr. (1917) *What a geologist can do in war,* Prepared for Geol. Com. Nat. Res. Council, J. P. Lippincott, Philadelphia.

Portlock, J. R., Maj. Gen. R. E. (1868) *A rudimentary treatise on geology,* 5th ed., London.

Powell, W. H. (1888) *The battle of the Petersburg Crater,* Battles and Leaders of the Civil War, vol. IV, 2d ed.

Price, P. H., and Woodward, H. P. (1942) *Geology and war,* Assoc. Am. State Geol., Jour., vol. 13, no. 4 (mimeographed); Am. Assoc. Petrol. Geol., Bull., vol. 26, p. 1832-1838.

Rosinski, Herbert (1943) *"Mackinder's democratic ideals and reality"—a review,* Infantry Jour., vol. 52, no. 1, p. 78-79.

Siegrist, Marie, and Platt, E. T. (1943) *Bibliography of military geology and geography,* 1st Supp., Geol. Soc. Am., New York.

Smith, G. O. (1918) *Thirty-ninth annual report of the Director of the United States Geological Survey to the Secretary of the Interior, for the fiscal year ended June 30, 1918,* Washington.

Sonne, Erich (1936) *Geologische und militärgeologische Karten,* Preuss. Geol., Landesanstalt, Jahrb. 1935, Bd. 56, Heft 1, p. 192-195.

Sun Tzu (500 B.C.) *Art of war* (Translated by Lionel Giles), *Roots of strategy* (1940), ed. by Maj. T. R. Phillips, p. 21-63, Military Service Pub. Co., Harrisburg, Pa.

Van Hise, C. R. (1906) *The problems of geology,* Inter. Cong., Arts Sci., vol IV, p. 526, New York.

Villate, R. H. J. (1925) *Les conditions géographiques de la guerre; étude de géographie militaire sur le front française de 1914 a 1918,* 350 p., Payot, Paris.

Von Bülow, Kurd, Kranz, Walter, and Sonne, Erich (1938) *Wehrgeologie,* 178 p., 164 figs., Quelle and Meyer, Leipzig.

War Department (1940a) *Engineer Field manual—Field fortifications, FM 5-15, Sect. 2, Terrain appreciation,* Pars. 8-13, p. 6-21, Washington. See also *FM 101-5, Staff officers Field manual, Form 4, Tactical study of the terrain,* p. 94; *Appendix II, Terrain appreciation,* p. 129-138.

War Department (1940b) *Staff Officers' field manual—The staff and combat orders*, FM 101-5, p. 90, 125-128, Washington.

Wasmund, Erich (1937) *Wehrgeologie in ihrer Bedeutung für die Landesverteidigung*, 103 p., Mittler and Sohn, Berlin.

Wilser, Julius von (1923-1929) *Die Kriegsschauplätze 1914-1918, geologisch dargestellt*, Hefte 1-10, 12-14, Gebr. Borntraeger, Berlin.

Wilson, Capt. A. S. (1937) *The scientific method of reasoning*, Royal Eng. Jour., vol. 51, p. 240.

U. S. Geological Survey, Washington, D. C.
Manuscript received by the Secretary of the Society, June 14, 1943.
Published with permission of the Director, U. S. Geological Survey.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 54, PP. 1195-1210 AUGUST 1, 1943

BIBLIOGRAPHY ON THE INTERPRETATION OF AERIAL PHOTOGRAPHS AND RECENT BIBLIOGRAPHIES ON AERIAL PHOTOGRAPHY AND RELATED SUBJECTS

BY GENEVIEVE C. COBB

CONTENTS

Page
Subject index to the bibliography 1195
Bibliography on the interpretation of aerial photographs 1197
Recent bibliographies on aerial photography and related subjects 1209

FOREWORD

Aerial photography has assumed such importance in the fields of science, industry, and war that it is necessary for many persons with little or no knowledge of this subject to make use of it either in teaching or practice. The literature on the reading and interpretation of aerial photographs is not voluminous, but it is so widely scattered through such diverse scientific and technical journals and books that it is difficult for an individual to assemble it quickly for study or use.

This bibliography lists the most useful references in those fields in which aerial photographs are used. It is by no means complete. For those who wish to search further there is included a list of recent bibliographies on aerial photography which contain many references on interpretation. The subject index provides a rough classification of the references under 11 general groups.

The collection of the material for this bibliography was made possible by the financial assistance of the Geology Department of Princeton University, which the compiler gratefully acknowledges.

GENEVIEVE C. COBB, Compiler.

SUBJECT INDEX TO THE BIBLIOGRAPHY

Archaeology

Cassan; Crawford 1923, 1924, 1928, 1929, 1938; Curwen; Ewald; Hansa Luftbild; Mackay; Poidebard 1932, 1934, 1939; Schmidt; Shippee; Thomas 1920.

Camouflage

Arnold 1939; Finch 1932; MacKenzie; Root.

Forestry

Andrews; Bourne 1928, 1931; Canada; Champion; Foster; Kemp; Lee 1941; Lobeck 1933; Lovejoy; Robbins 1929, 1931, 1934; Ryker; Scott; Seely; Stamp; U. S. Dept. Agriculture; White; Wieslander; Wilcox.

General

Bagley; Bouché 1920; Brenot; Canada; Clay; Clerc 1919, 1920; Cochran-Patrick; Eardley; Eliel; Fairchild; Fischer; Fiske; Goussot; Great Britain Air Ministry; Hart 1937, 1940; Heavey; Hemming; Hotine 1931; Infantry Journal; Ives; MacClintock; MacLeod 1919; Matthes 1924; Military Service Pub. Co. 1942, 1943; Mollandin; Narraway; Ponzian; Portillo; Reeves; Robbins 1934; Simons; Smith, H. 1928, 1943; Stokes; Talley; Taylor; Thomas 1920, 1924; Underhill; U. S. Cavalry School; U. S. War Dept.; Vivian; Volla; Whitemore; Winchester.

Geography

Ahrens; Blache 1920, 1921; Canada; Chevalier 1930; Hansa Luftbild; Johnson; Lee 1920, 1922; Light; Lobeck 1933, 1939; Lockey; Madigan; Pennès; Poidebard 1929; Purser; Reeves; Rengarten; Reyniers; Rich 1939, 1941, 1942; Scott; Smith, H. 1941, 1942; Thomas 1920.

Geology

Abrams; Ahrens; Alcock; Aufrère; Belfiore; Berkaloff 1937, 1938; Besairie; Blakemore; Blazing . . .; Blondel 1936, 1937; Bonnes; Bourne 1928, 1931; Bruce, E.; Bruce, H.; Cooper; Cozzens; Desjardins 1938, 1939; Eardley 1941, 1942; Edgar Tobin; Eliel 1927, 1928, 1929, 1930, 1936; English; Farrington; Field; Fitch; Galitsky; Gill 1931, 1932, 1933; Greenly; Gwynne; Hemming 1933; Hotine 1938; Howard 1940; Jaggar; Johnson; Kennedy; Lahee; Lee 1922; Lobeck 1933, 1939; Loel 1927, 1938, 1941; Logan; MacClintock; Madigan; Maple; Marchesini; Matthes 1924, 1928; Melton 1936, 1939, 1940; Military Service Pub. Co. 1938; Milner; Mogg; Moore; Nichols; Nouhuys; Pennès; Poidebard, R. 1929; Portillo; Putnam; Rea; Reed; Reeves; Reyniers; Rich 1928, 1934, 1939, 1941, 1942; Robbins 1934; Rockie; Rydlun; Scherpbier; Simons; Smith, H. 1942, 1943; Stokes; Taylor; Thomas 1920; Tieje; Walker 1926, 1929, 1934; Washburn; Willett; Williams; Willis; Woolnough 1933, 1934, 1937; Zuber.

Hydrography

Berkaloff 1938; Birdseye; Blakemore; De L'Isle; Haynie; Ives; Jessen; Lee 1922; Melton 1936; Putnam; U. S. Dept. Agriculture; Volmat.

Military

Arnold 1939, 1941; Belcher; Bouché 1920; Brooke; Carlier; Clark; Clerc 1920; Duff; Eardley; Finch 1932; France; Fuller; Goussot; Great Britain; Hammerton; Harrow; Haynie; Heavey; Infantry Journal; Ives; Lloyd; MacKenzie; MacLeod 1919, 1920; Military Service Pub. Co.; Pepin; Porter; Putnam; Reeves; Reyniers; Rich 1942; Roberts; Rockie; Root; Shepherd; Smith, D.; Thomas 1920; U. S. War Dept.; Vivian; Volla.

Oil

Bignell; Bowen; Bruce, H.; Edgar Tobin; Eliel 1929, 1936; Hemming 1933; Hotine 1938; Loel 1927; Maple; Williams; Woolnough 1933, 1934.

Soil

Abrams; Ahrens; Belcher; Blakemore; Bouché 1921; Bourne 1931, 1932; Crawford 1929; Curwen; Gaty; Greenly; Lowdermilk; Millar; Nichols; Prescott; Rich 1934; Robbins 1931, 1934; Rockie; Stamp; Troll; U. S. Dept. Agriculture.

Vegetation

Blakemore; Bouché 1921; Bourne 1928, 1931; Burks; Chevalier 1930; Crawford 1929; Gaty; Greenly; Kemp; Lobeck 1933; Lovejoy; Matthes 1924; Mogg; Prescott; Robbins 1931, 1934; Root; Stamp; Troll; U. S. Dept. Agriculture; Walker 1926, 1929; Wieslander.

BIBLIOGRAPHY ON THE INTERPRETATION OF AERIAL PHOTOGRAPHS*

Abrams, Talbert. Mapping Michigan for geologists. Engineering & Mining Journal v. 136, no. 11, p. 564-565, Nov. 1935.

Ahrens, T. P. The utilization of aerial photographs in mapping and studying land features. Resettlement Administration. Land Utilization Division. Land-use Planning Section. Publication no. 6. Wash., Oct. 1936. 27 pp.

Alcock, Frederick J. Airplanes an aid in geologic studies. Engineering & Mining Journal v. 136, no. 11, p. 546-547, Nov. 1935.

———. Geological mapping with aeroplanes assistance. Engineering Journal, Montreal v. 18, no. 12, p. 593, Dec. 1935.

Andrews, G. S. Tree heights from air photographs by simple parallax measurements. Forestry Chronicle, Vancouver v. 12, no. 2, p. 152-197, June 1936.

***Arnold, R. R.** Concealment of motor vehicles. Military Engineer v. 31, no. 179, p. 329-334, Sept.-Oct. 1939.

———. Military uses of aerial photographs. Photogrammetric Engineering v. 7, no. 2, p. 90-95, April-June 1941.

Aufrère, Léon. Utilisation de la photographie zénithale dans l'étude morphologique et dans la cartographie des dunes. Congrès International de Géographie, Paris 1931, Compte Rendu t. 1, p. 155-162, 1933.

Bagley, James W. Aerophotography and aerosurveying. N. Y., McGraw Hill, 1941. 324 pp. $3.50.

***Belcher, Donald J.** Use of aerial photographs in war-time soils engineering. Roads & Streets v. 85, p. 35-37, July 1942.

Belfiore, Placido. Geologia e fotogrammetria. Rivista del Catasto e dei Servizi Tecnici Erariali v. 5, no. 1, p. 13-44, Jan.-Feb. 1938.

Berkaloff, E. Essais de cartographie géologique aérienne en Tunisie. La Chronique des Mines Coloniales (Bur. d'Études Géol. & Min. Coloniales) Paris an. 6, no. 63, p. 317-325, Juin 15, 1937.

———. Utilisation des aeronefs pour la cartographie géologique, hydrogéologique et minière en Tunisie. Congrés Mondial du Pétrole, Paris 1937, Compte Rendu t. 1, p. 401-410, 1938.

*The most important references are marked by an asterisk before the author's name.

Besairie, Henri. L'emploi de l'avion pour les levés géologiques à Madagascar. La Chronique des Mines Coloniales (Bur. d'Études Géol. et Min. Coloniales), an. 6, no. 62, p. 264-265, Mai 15, 1937.

Bignell, L. G. E. Aerial survey is essential in modern oil operations. Oil & Gas Journal v. 36, no. 1, p. 70, 74, May 20, 1937.

Birdseye, Claude H. Flood measurements by aerial photography. Canadian Surveyor v. 6, no. 1, p. 10-11, July 1937.

Blache, Jules. Quelques aspects des montagnes Marocaines. Revue de Géographie Alpine v. 8, no. 2, p. 225-258, 1920.

———. Modes of life in the Moroccan countryside. Interpretations of aerial photographs. Geographical Review v. 11, no. 4, p. 477-502, Oct. 1921.

Blakemore, Emmett F., Jr. Drainage controls in the Austin chalk cuesta area of Dallas, Texas. Field & Laboratory v. 7, no. 2, p. 57-66, May 1939.

Blazing the rock-hounds' trails. Standard Oil Bulletin v. 15, no. 8, p. 2-9, Dec. 1927; Oil Bulletin, Calif. Chamber of Mines & Oil v. 14, no. 2, p. 131-133, 143, Feb. 1928.

Blondel, Fernand. L'emploi de l'avion pour les recherches géologiques et minières dans les pays neufs. Le Génie Civil, Paris v. 109, no. 25, p. 545-549, Dec. 19, 1936—résumé of paper in: La Chronique des Mines Coloniales (Bur. d'Études Géol. et Min. Coloniales) an. 6, no. 58, p. 2-15, Jan. 1937, Additif no. 59, p. 82, Feb. 1937; Bulletin de Photogrammétrie an. 7, no. 3, p. 65-77, May-June 1937.

Bonnes, A. Aviation et géologie. Revue du Ministère de l'Air, Paris v. 2, no. 20, p. 993-1016, Aug. 15, 1936.

Bouché, Henri. La photographie aérienne, arme de guerre, outil de la paix. Société d'Encouragement pour l'Industrie Nationale, Paris, Bulletin t. 132, no. 4, p. 464-486, July-Aug. 1920.

———. La photographie aérienne et la vie agricole; cadastre et remembrement. L'Aeronautique, Paris, v. 3, no. 21, p. 71-76, Feb. 1921.

Bourne, Ray. Aerial survey in relation to the economic development of new countries, with special reference to an investigation carried out in Northern Rhodesia. Oxford Forestry Memoirs no. 9, Oxford, Clarendon Press, 1928. 35 pp.

*———. Regional survey and its relation to stocktaking of the agricultural and forest resources of the British Empire. Oxford Forestry Memoirs no. 13, Oxford, Clarendon Press, 1931. 169 pp.

*———. Air survey in relation to soil survey. Imperial Bureau of Soil Science, Technical Communication no. 19, July 1931. 18 pp.; Indian Journal of Agricultural Science, Calcutta v. 2, p. 204-220, April 1932.

Bowen, R. A. Aerial photographer is rendering valuable service to oil industry. Oil & Gas Journal v. 36, no. 24, p. 28-29, Oct. 28, 1937.

* **Brenot, L. E.** Interpretation of vertical air photographs. Canadian Surveyor v. 5, no. 9, p. 2-7, July 1936.

* **Brooke, Mark.** Interpretation of aerial photographs. Military Engineer v. 16, no. 87, p. 213-215, Discussion p. 215-217, May-June 1924; Photo-era Magazine v. 53, p. 245-250, Nov. 1924.

Bruce, Everend L. The possibility of the use of sea-planes in preliminary mapping of pre-Cambrian areas. Canadian Institute of Mining & Metallurgy, Monthly Bulletin no. 118, p. 224-229, Feb. 1922.

Bruce, Herbert T. Photogrammetry and the oil engineer. Oil Weekly v. 98, no. 1, p. 19-22, June 10, 1940.

Burks, G. F. and R. C. Wilson. A vegetation inventory from aerial photographs. Photogrammetric Engineering v. 5, no. 1, p. 30-42, Jan.-Mar. 1939.

Canada. Dept. of the Interior. Surveys Branch. The use of aerial photographs for mapping. Topographical Survey Bulletin no. 62, Ottawa, 1932. 80 pp.

Carlier, André H. La photographie aérienne. Paris, Librairie Delagrave, 1921. 204 pp.

Cassan, Stanley. Archaeology from the air. Scientific American v. 155, p. 130-132, Sept. 1936.

Champion, F. W. Air-survey of forests. Indian Forester v. 59, no. 1, p. 12-21, Jan. 1933.

Chevalier, Auguste. Les applications de la photographie aérienne a l' étude de la géographie botanique. Compte Rendu Sommaire des Séances de la Société de Biogeographie, Paris v. 7, no. 57, p. 64-66, June 20, 1930.

———. L'aviation au service de l'agriculture tropicale et de la géographie botanique. Revue de Botanique Appliquée et d'Agriculture Tropicale, Bulletin v. 10, no. 106, p. 353-356, Juin 1930.

Clark, W. & R. R. Arnold. Military uses of photography from the air. American Photography v. 36, p. 28-32, Sept. 1942; Military Engineer v. 33, no. 191, p. 357-362, Sept. 1941.

Clay, W. H. Christy. Air survey especially in relation to railways. 5th International Congress of Surveyors in London, Proceedings p. 256-269, 1934.

Clerc, L. P. Estimation of the height of objects by the measurement of their cast shadows in aerial photography. British Journal of Photography v. 66, p. 296-297, May 30, 1919.

———. Applications de la photographie aérienne (lecture et interpretation stereoscopie aérienne, appareils et methodes pour la photographie aérienne). Paris, Octave Doin, 1920. 350 pp.

Cochran-Patrick, C. K. Present practice in aerial survey. Society of Engineers, London, Transactions for 1931, p. 177-197, Discussion p. 197-204. (Reprinted as pamphlet by Aircraft Operating Co.)

Cooper, William S. The history of the upper Mississippi River in late Wisconsin and postglacial time. Minnesota Geological Survey, Bulletin 26, Univ. of Minn. Press, 1935. 116 pp. (Chap. 5. The dunes.)

***Cozzens, W. L.** Aerial mapping in relation to geological exploration. Pacific Mineralogist v. 4, no. 1, p. 13-28, June 1937.

Crawford, Osbert G. S. Air survey and archaeology. Geographical Journal v. 61, no. 5, p. 342-366, 1923; Great Britain, Ordnance Survey, Professional Paper n.s. no. 7, 1924. 39 pp.; 2d ed. 1928. 42 pp.

———. Aiding archaeology from the air. Aircraft Engineering, London v. 1, no. 5, p. 166-168, July 1929.

———. Air photography for archaeologists. Great Britain, Ordnance Survey, Professional Paper n.s. no. 12, 1929. 44 pp.

———. Luftbildaufnahmen von archäologischen Bodendenkmälern in England. Luftbild und Luftbildmessung nr. 16, p. 9-18, Berlin, Hansa Luftbild, 1938.

——— **& A. Keiller.** Wessex from the air. Oxford, Clarendon Press, 1928. 263 pp. 50s.

Curwen, Eliot C. Air-photography and economic history: the evolution of the cornfield. Economic History Society. Bibliographies and pamphlets, no. 2, London, 1930. 31 pp.; 2d ed., London, Black, 1938. 32 pp.

De L'Isle, Rollet. Report on the employment of aerial photography in connection with surveying by the Hydrographic Service of the French navy. The Hydrographic Review, Monaco v. 1, no. 1, p. 73-87, Mar. 1923.

Desjardins, Louis & S. G. Hower. A technique for geologic, topographic and structural mapping from aerial photographs. Aero Exploration Co., Tulsa, Okla. 1938.

———. Geologic mapping from air. Oil and Gas Journal v. 37, no. 52, p. 44-46, 59, May 11, 1939.

———. Geologic, topographic and structural mapping from aerial photographs. American Petroleum Institute volume on finding and producing oil, 1st ed. p. 29-33, Dallas, 1939.

Dickerson, Roy E. Trends of Pleistocene ocean currents across the Florida Everglades. Geographical Review v. 32, p. 135-139, Jan. 1942.

Duff, A. C. The interpretation of air photographs. Royal Engineers Journal v. 44, p. 288-295, June 1930.

Eardley, Armand J. Interpretation of geologic maps and aerial photographs. Ann Arbor, Mich., Edwards Bros., 1941. 99 pp. $1.50.

*———. Aerial photographs, their use and interpretation. N. Y., Harper, 1942. 203 pp. $2.75.

Edgar Tobin Aerial Surveys. Aerial maps and oil geology. San Antonio, Texas, Edgar Tobin Aerial Surveys, 1932. 15 pp.

Eliel, Leon T. Aerial maps find new applications. Military Engineer v. 19, no. 107, p. 364-369, Sept.-Oct. 1927.

———. Faults undiscovered on the ground revealed by aerial maps. Oil Field Engineering v. 5, p. 24-27, 64, Jan. 1929.

———. Putting wings on the geologists' mule. Oil & Gas Journal v. 27, no. 22, p. 122, Oct. 18, 1928; v. 27, no. 36, p. 78, 87-88, Jan. 24, 1929.

———. Aerial photography proves its importance to California geologists. Oil Bulletin, Los Angeles, v. 15, p. 1177-1181, Nov. 1, 1929.

*———. Aerial photography and its importance to California geologists. California Dept. of Natural Resources, Division of Mines "Mining in California" v. 26, no. 1, p. 64-71, Jan. 1930.

———. Aerial reconnaissance and contour mapping in mining. American Institute of Mining & Metallurgical Engineers, Transactions v. 126, p. 560-574, Discussion p. 579-581, 1937; A. I. M. E. Technical Publication 756, p. 4-20, Discussion p. 26-27, 1936.

English, Walter A. Use of aeroplane photographs in geologic mapping. American Association of Petroleum Geologists, Bulletin v. 14, no. 2, p. 1049-1058, Aug. 1930.

Ewald, Erich. Einsatz des Luftbildes fur die vorgeschichtliche forschung in Deutschland. Luftbild und Luftbildmessung nr. 16, p. 19-22, Berlin, Hansa Luftbild, 1938.

———. Ergebnis der veranstaltung über Luftbild und vorgeschichtliche forschung am 21 und 22 Marz 1938. Luftbild und Luftbildmessung nr. 16, p. 23-24, Berlin, Hansa Luftbild, 1938.

Fairchild Aerial Surveys, Inc. The stereoscope in aerial photography. Fairchild Aerial Surveys, Inc. Bulletin no. 4, 1925. 8 pp.

Farrington, J. L. A geological application of aerial survey. Geological Society of South Africa, Transactions v. 38, p. 57-71, Jan.-Dec. 1935.

Field, Richard M. and H. T. Stetson. Map reading and avigation. N. Y., Van Nostrand, 1942. 129 pp. $2.50.

Finch, H. A.—Field camouflage and aerial photography. Military Engineer v. 24, no. 133, p. 30-35, Jan.-Feb. 1932.

——. Notes on camouflage testing in Texas. Military Engineer v. 31, no. 176, p. 112-114, Mar.-April 1939.

Fischer, Eberhard. Das Luftbildwesen. Berlin, Bernard, 1936. 262 pp. (Der dienst in der luftwaffe, bd. 2.)

Fiske, Harold C. Topography from aerial photographs. Military Engineer v. 16, no. 89, p. 399-408, Sept.-Oct. 1924; Fairchild Aerial Surveys, Inc. Bulletin no. 2.

Fitch, A. A. Geological observations on air photographs of the Peace River area, British Columbia. Photogrammetric Engineering v. 8, no. 2, p. 156-159, April-June 1942.

Foster, Ellery. The use of aerial photographs in mapping ground conditions and cruising timber in the Mississippi River bottom lands. U. S. Forest Service, Southern Forest Experiment Station, Occasional Paper no. 37, Nov. 1934. 7 pp.

France. Armée. Grand Quartier Genéral Des Armées. État Major. Notes sur l'interpretation des photographies aériennes. Dec. 30, 1916. 61 pp.

——. **Armée. Grand Quartier Genéral Des Armées du Nord et du Nord-est. Etat-Major.** Étude et exploitation des photographies aériennes. Paris, 1918. Pt. 1. Texte, 80 pp. Pt. 2. Planches. (English translation for American Expeditionary Forces, Paris, 1918.)

Fuller, Theodore A. Interpretation of aerial photographs by company officers. Military Engineer v. 34, no. 195, p. 26-29, Jan. 1942.

Galitsky, V. V. Aerial photography in the geological mapping of the paleozoic deposits of the Kara-Tau Mountain range (Turkestan). Problems of Soviet Geology v. 5, no. 10, p. 962-975, 1935. (In Russian.)

Gaty, John P. Aerial photography. American Photography v. 29, no. 4, p. 248-251, April 1935.

***Gill, Donald.** The aeroplane in geological and mineral exploration. South African Mining & Engineering Journal v. 42, pt. 2, p. 319-321, 347-348, 375-376, 407-408, Nov. 28-Dec. 19, 1931.

——. The interpretation of geology from aerial photographs. South African Mining & Engineering Journal v. 42, pt. 2, p. 466-469, Jan. 9, 1932 (I. Messina), v. 43, pt. 1, p. 164-166, April 16, 1932 (II. Sheba Hills).

*——. Aerial survey in relation to economic geology. Institution of Mining & Metallurgy, Bulletin no. 337, p. 1-56, Oct. 1932, Discussion in Bull. no. 338, p. 37, Nov. 1932, no. 339, p. 1-31, Dec. 1932; Royal Aeronautical Society, Journal v. 37, no. 267, p. 227-264, Discussion p. 264-287, Mar. 1933.

——. Air survey in relation to economic geology. Institution of Mining & Metallurgy, Transactions v. 42, p. 81-136, Discussion p. 136-175, 1933.

Goussot, C. M. Précis de photographie aérienne. Paris, Chiron, 1923. 185 pp.

Great Britain. Air Ministry. Air photography. Pt. 1. Organisation and training. Air Publication 1354, rev. Feb. 1936, rep. Nov. 1939, London, 1940. 3s.

——. **General Staff (Intelligence) General Headquarters.** Notes on the interpretation of aeroplane photographs. 3d ed., Feb. 1918. 11 pp. & 42 plates.

——. **War Office.** Manual of map reading, photo reading and field sketching. London, 1929, Reprinted with amendments 1939, 1940. 166 pp. 3s 6d.

Greenly, Edward and H. Williams. Methods in geological surveying. London, Murby, 1930. 420 pp. 17s 6d.

Gwynne, Charles S. Swell and swale pattern of the Mankato lobe of the Wisconsin drift plain in Iowa. Journal of Geology v. 50, no. 2, p. 200-208, Feb.-Mar. 1942.

Hammerton, Sir John. ABC of the R. A. F. London, Amalgamated Press, n. d. (Sect. 3, p. 97-98 How to read air photographs.)

***Hansa, Luftbild.** Luftbild und Luftbildmessung. Berlin, Hansa Luftbild, nr. 13. Luftbild-Lesebuch. 1937. 66 pp.; nr. 14. Luftbild-Topographie. 1936. 79 pp.; nr. 16. Luftbild und Vorgeschichte. 1938. 84 pp.

Harrow, Rex. Airmen cannot believe what they see. Illustrated World v. 32, p. 178-180, 304, Oct. 1919.

Hart, Cecil A. Air survey as an aid to economic development. Institution of Municipal & County Engineers, London, Journal v. 63, no. 24, p. 1593-1607, May 25, 1937.

*———. Air photography applied to surveying. N. Y., Longmans Green, 1940. 366 pp. $7.50.

Haynie, J. M. Naval uses of aerial photography. U. S. Naval Institute, Proceedings v. 67, no. 465, p. 1567-1574, Nov. 1941.

Heavey, William F. Map and aerial photo reading simplified. 4th ed. Harrisburg, Pa., Military Service Publ. Co., 1942. 104 pp. $1.00.

***Hemming, H.** Air survey work: its various aspects and uses. The Association of Special Libraries & Information Bureaux, Report of Proceedings of the 10th Conference, 1933. p. 120-136, London, 1933.

*———. Aircraft in relation to petroleum technology: use for survey and transport. Institution of Petroleum Technologists, Journal v. 19, no. 112, p. 73-97, Discussion p. 97-116, Feb. 1933; Royal Aeronautical Society, Journal v. 37, p. 864-899, Oct. 1933.

Hotine, Martin. Surveying from air photographs. N. Y., R. Smith, 1931. 250 pp. $8.

———. Aerial reconnaissance, In: Dunstan, A. E., ed. Science of petroleum. v. 1, p. 284-290, N. Y., Oxford Univ. Press, 1938.

Howard, Waldorf V. Aerial photographs furnish valuable aid to geologists. Oil & Gas Journal v. 38, no. 49, p. 52-53, April 18, 1940.

———. Aerial photographic surveys valuable on Gulf Coast. Oil & Gas Journal v. 38, no. 48, p. 194-195, April 25, 1940.

Infantry Journal. Map reconnaissance; a practical treatise on map reading, interpretation of aerial photographs and military sketching; with numerous practical exercises. Wash., D. C. National Service Publ. Co., 1930. 202 pp.

***Ives, Herbert E.** Airplane photography. Phila., Lippincott, 1920. 422 pp. $4.

Jaggar, Thomas A., Jr. Airplanes for volcanology. The Volcano Letter, Hawaii no. 270, p. 1-4, Feb. 27, 1930.

Jessen, A. O. Empleo de la fotografia aérea en los levantamientos hidrográficos. Anuario Hidrográfico de la Marina de Chile, Santiago v. 35, p. 517-553, 1930.

Johnson, George R. & R. R. Platt. Peru from the air. American Geographical Society, Special Publication no. 12, N. Y., 1930. 159 pp. $5.

Kemp, R. C., C. G. Lewis, C. W. Scott & C. R. Robbins. Aero photo survey and mapping of the forests of the Irrawaddy Delta. Burma Forest Bulletin no. 11, Misc. Ser. 1. Maymyo, Burma, Jan. 1925. 43 pp.

Kennedy, Mel S. Prospecting by air. Western Flying, Los Angeles v. 7, no. 6, p. 57-59, 132, June 1930.

Lahee, Frederic H. Field geology. 4th ed. N. Y., McGraw Hill, 1941. 853 pp. $5. (Pt. IV, p. 536-558 on Airplane mapping.)

Lee, Howard C. Aerial photography, a method for fuel type mapping. Journal of Forestry v. 39, no. 6, p. 531-533, June 1941.

Lee, Willis T. Airplanes and geography. Geographical Review v. 10, p. 310-325, Nov. 1920.

*——. The face of the earth as seen from the air. American Geographical Society, Special Publication no. 4, N. Y., 1922. 110 pp. $4.

Light, Richard U. Focus on Africa. American Geographical Society, Special Publication no. 25, N. Y., 1941. 228 pp. $5.

Lloyd, H. A. Classification of the ground from the air. Flying v. 9, no. 11, p. 680-682, Dec. 1920; Geographical Journal v. 56, no. 2, p. 99-105, Discussion p. 105-107, 1920.

***Lobeck, Armin K.** Airways of America. Guidebook no. 1, The United Air Lines. A geological and geographical description of the route from New York to Chicago and San Francisco. N. Y., Geographical Press, Columbia Univ., 1933. 207 pp. $2.50.

——. Geomorphology. An introduction to the study of landscapes. N. Y., McGraw Hill, 1939. 731 pp. $4.50.

Lockey, B. The interpretation of Ordnance survey maps and geographical pictures. London, Philip, 1937. 32 pp. 2 s.

Loel, Wayne. Aerial mapping of geologic features. Oil Bulletin, Chamber of Mines & Oil, California v. 13, no. 5, p. 461, May 1927.

*——. Use of aerial photographs in geologic mapping. American Institute of Mining & Metallurgical Engineers, Transactions v. 144, p. 356-409, 1941; Mining Technology v. 2, no. 2, (A. I. M. E. Technical Publication 890) Mar. 1938. 54 pp.

Logan, Jack. Aerial photography in geological and geophysical work. Oil Weekly v. 64, no. 10, p. 17-20, 24, 26, Feb. 19, 1932.

Lovejoy, Omar H. A cover map based on air photographs, Emmet Co., Mich. Michigan Academy of Sciences, Arts & Letters, Papers v. 26, p. 407-410, 1940.

Lowdermilk, W. C. Use of aerial mapping in soil conservation studies. Civil Engineering v. 8, no. 9, p. 605-607, 1938.

MacClintock, Paul. [Outlines for course in Map and Aerial Photograph Interpretation] Geology Dept., Princeton Univ., 1942: How to examine aerial photographs. 4 pp. (mimeo.); Geology of the terrain as shown on aerial photographs. 4 pp. (mimeo.)

Mackay, Dorothy. The airman as archaeological scout. Asia v. 31, no. 8, p. 484-491, Aug. 1931.

MacKenzie, Alister. The common sense of camouflage. Military Engineer v. 26, no. 148, p. 288-292, July-Aug. 1934.

Macleod, Malcolm N. Mapping from air photographs. British Journal of Photography v. 66, p. 503-505, 518-522, Aug. 29, Sept. 5, 1919.

——, comp. Mapping from air photographs. Great Britain, General Staff, War Office, London, 1920. 66 pp. 4 s.

Madigan, C. T. An aerial reconnaissance into the south-eastern portion of Central Australia. Royal Geographical Society of Australasia, South Australian branch v. 30, p. 83-108, Session 1928-1929, 1930.

Maple, A. F. Discovering oil from 20,000 feet. World Petroleum v. 7, no. 4, p. 181-184, April 1936.

Marchesini, Enrico. Impiego dell'aeroplano come mezzo di complemento nei rilevamenti geologici. Rivista Aeronautica v. 10, no. 9, p. 467-478, Sept. 1934.

———. Analisi geologica di aerofotogrammi. L'Universo Anno 19, n. 2, p. 103-112, Feb. 1938.

Matthes, Gerard H. Aerial photography as an aid to better map making. Engineering News Record v. 92, no. 1, p. 25-27, Jan. 3, 1924.

———. Aerial photography as an aid in geological studies. American Institute of Mining and Metallurgical Engineers, Transactions v. 76, p. 321-336, 1928.

Melton, Frank A. An empirical classification of flood-plain streams. Geographical Review v. 26, no. 4, p. 593-609, Oct. 1936.

———. Aerial photographs and the first course in geology. Photogrammetric Engineering v. 5, no. 2, p. 74-77, April-June, 1939.

———. A tentative classification of sand dunes, its application to dune history in the southern High Plains. Journal of Geology v. 48, no. 2, p. 113-174, Feb.-Mar. 1940.

Military Service Publishing Co. Map reading, interpretation of aerial photographs, military sketching. 2d ed., Harrisburg, Pa., Military Service Publ. Co., 1938. 199 pp. $1.25.

———. Map and aerial photo reading simplified. 4th ed. Harrisburg, Pa., Military Service Publ. Co., 1942. 104 pp.

———. Map and aerial photograph reading—complete. Harrisburg, Pa., Military Service Publ. Co., 1943. 189 pp. $1.

Millar, Charles E. The use of aerial photographs in the Michigan land economic survey. American Soil Survey Association, Bulletin 13, p. 82-85, May 1932.

* **Milner, H. B.** Geology from the air. Queensland Government Mining Journal v. 30, no. 348, p. 202-204, May 15, 1929; Mining Magazine v. 40, p. 188-191, Mar. 1929.

Mogg, A. O. D. The flora of Vryburg district in relation to geology, and a preliminary account of the flora of Pretoria in relation to geology. 15th International Geological Congress, South Africa, 1929. Compte Rendu v. 2, sect. 7, p. 638-650, Pretoria, 1930.

———. A preliminary account of the flora of Pretoria in relation to the geology. 15th International Geological Congress, South Africa, 1929. Compte Rendu v. 2, sect. 7, p. 651-669, Pretoria, 1930.

Mollandin, André. Le vol en avion, Ses joies, ses leçons. Paris, Frazier-Soye, 1935. 378 pp. 150 aerial photos.

Moore, A. J. Spotting mineral deposits by airplane. Engineering & Mining Journal v. 128, p. 812-813, Nov. 23, 1929.

Narraway, A. M. Aerial surveying as applied to engineering problems. Engineering Institute of Canada, Journal v. 13, no. 3, p. 171-178, Mar. 1930.

Nichols, D. A. Solifluction and other features in northern Canada shown by photographs from the air. Royal Society of Canada, Transactions 3d ser. v. 26, sect. 4, p. 267-275, 1932.

* **Nouhuys, J. J. van.** Geological interpretation of aerial photographs. American Institute of Mining & Metallurgical Engineers, Transactions v. 126, p. 607-624, 1937; Mining Technology v. 1, no. 4, (A. I. M. E. Technical Publication 825) July 1937. 18 pp.

Pennès, P. & Lt. Spillmann. Les pays inaccessibles du Haut Draa (Un essai d'exploration aérienne en collaboration avec les Services des Affaires Indigènes du Maroc). Revue de Géographie Marocaine v. 8, no. 1-2, 62 pp. & atlas geographique, 1929.

Pepin, E. A lecture on the study and interpretation of aerial photographs. U. S. War Dept. Office of Chief Signal Officer, Information Section—Air Division. Dec. 1, 1917. 18 pp. (mimeo.)

Poidebard, Antoine. La trace de Rome dans le désert de Syrie. Les limes de Trajan a la conquête Arabe. Recherches aériennes (1925-1932). Paris, Geunther, 1934. Texte 213 pp. Atlas.

——. Un grand port disparu Tyr, recherches aériennes et sous-marines 1934-1936. Paris, Geunther, 1939. Texte 78 pp. Atlas 29 pl.

Poidebard, R. P. A. Reconnaissance aérienne au Ledja et au Safa (Observations geographiques). La Geographie v. 52, p. 1-17, 1929.

——. Photographie aérienne et archéologie recherches en steppe Syrienne (1925-1931). Bulletin de Photogrammétrie v. 2, no. 2, p. 35-48, 1932.

Ponzian, Mario. Fotografia dall' Aereo. L'Universo v. 17, no. 7, p. 469-490, Luglio 1936.

Porter, Harold E. (pseud. Holworthy Hall) Aerial observation: the airplane observer, the balloon observer and the army corps pilot. N. Y., Harper, 1921. 355 pp. $4.

——. (pseud. Holworthy Hall) Photographic interpretation from the air. U. S. Air Service, N. Y. v. 5, no. 4, p. 28-29, May 1921. (rep. from his book: Aerial observation)

Portillo, Gregorio A. Contribución al estudio de la aviación civil y de sus aplicaciones. Buenos Aires, Aviacion, 1938. 134 pp.

Prescott, J. A. & J. K. Taylor. The value of aerial photography in relation to soil surveys and classification. Council for Scientific & Industrial Research (Australia), Journal v. 3, no. 4, p. 229-230, Nov. 1930.

Purser, Ralph. Geography from the air. Canadian Geographical Journal v. 22, no. 3, p. 147-149, Mar. 1941.

Putnam, William C. Map interpretation with military applications. N. Y., McGraw Hill, 1943. 67 pp. $1.25.

Rea, Henry C. Photogeology. American Association of Petroleum Geologists, Bulletin v. 25, no. 9, p. 1796-1800, Sept. 1941.

Reed, J. C. The use of airplane photographs in the geologic study of the Chichagof mining district, Alaska. Photogrammetric Engineering v. 6, no. 1, p. 35-44, Jan.-Mar. 1940.

***Reeves, Dache M.** Aerial photographs, characteristics and military applications. N. Y., Ronald, 1927. 307 pp. $5.

Rengarten, P. A. L'utilisation des documents du leve photographique par avion pour l'étude de la geomorphologie dans les differentes conditions physico-geographiques. Societe de Geographie de l'URSS, Izvestia v. 71, no. 6, p. 887-896, 1939. (Russian)

Reyneirs, Lt. De l'aviation employée comme mode d'exploration scientifique. Geologie. Revue de Géographie Marocaine, Casablanca 14 an., No. 4, p. 177-189, Dec. 1930.

Rich, John L. Jointing in limestones as seen from the air. American Association of Petroleum Geologists, Bulletin v. 12, no. 8, p. 861-862, Aug. 1928.

Rich, John L. Soil mottlings and mounds in northeastern Texas as seen from the air. Geographical Review v. 24, p. 576-583, Oct. 1934.

———. A bird's-eye cross section of the central Appalachian Mountains and plateau: Washington to Cincinnati. Geographical Review v. 29, no. 4, p. 561-586, Oct. 1939.

———. Nitrate district of Tarapacá, Chile: an aerial traverse; with photographic record. Geographical Review v. 31, p. 1-22, Jan. 1941.

———. The aerial traverse; an application of aerial photography to geographic studies. Ohio Journal of Science v. 41, no. 3, p. 212-224, May 1941.

———. Military geology from the air. Science n.s. v. 95, no. 2474, p. 543-545, May 29, 1942.

———. The face of South America, an aerial traverse. American Geographical Society, Special Publication no. 26, N. Y., 1942. 299 pp. $4.

* **Robbins, Charles R.** Air survey and forestry. Empire Forestry Journal v. 8, no. 2, p. 205-228, 1929.

———. An economic aspect of regional survey. Journal of Ecology v. 19, no. 1, p. 25-33, Feb. 1931.

———. Economic uses of aerial survey. South African Institution of Engineers, Journal v. 32, no. 8 & 11, p. 155-164, Discussion p. 164-165, 232, Mar. 1934, v. 33, no. 2, p. 18-21, Sept. 1934.

———. The economics of aerial survey applied to geological problems. South African Mining and Engineering Journal v. 45, pt. 1, p. 369, 417, June 30, July 14, 1934.

———. Northern Rhodesia; an experiment in the classification of lands with the use of aerial photographs. Journal of Ecology v. 22, no. 1, p. 88-105, Feb. 1934.

Roberts, Leo B. Topographic mapping. Wash., D. C., Society of American Military Engineers, 1924. 150 pp. $1.50.

Rockie, W. A. Pitting on Alaskan farm lands. A new erosion problem. Geographical Review v. 32, p. 128-134, Jan. 1942.

* **Root, Ralph R.** Camouflage with planting. Chicago, R. F. Seymour, 1942. 79 pp. $1.50.

Rydlun, E. G. Aerial photography as applied to mining and geology. Engineering & Mining Journal v. 126, no. 6, p. 204-209, Aug. 11, 1928.

Ryker, Harrison C. Aerial photography. Method of determining timber species. The Timberman v. 34, no. 5, p. 11-17, Mar. 1933.

Scherpbier, B. & J. Krebs. Aerial survey in exploration work. Institution of Petroleum Technologists, Journal v. 24, no. 174, p. 225-232, April 1938.

Schmidt, Erich F. Flights over ancient cities of Iran. Chicago, Univ. of Chicago Press, 1940. 104 pp. $20.

* **Scott, C. W. & C. R. Robbins.** Report on aerial reconnaissance, stock-mapping and photography of the forests of the Tavoy and Mergui Districts (South Tenasserim Forest Division) Jan. to April 1925. Burma Forest Bulletin 13, Misc. ser. no. 2, Rangoon, Feb. 1926. 76 pp.

Seely, H. E. Aerial photography in forest surveys. Empire Forestry Journal, London v. 13, no. 2, p. 244-247, Dec. 1934.

———. The use of air photographs for forestry purposes. Forestry Chronicle, Vancouver v. 11, no. 4, p. 287-293, Dec. 1935.

———. Air photographs as used by the Dominion Forest Service. Journal of Forestry v. 36, p. 1035-1038, Oct. 1938.

Seely, H. E. Determination of tree heights from shadows in air photographs. Canada, Dominion Forest Service, Aerial Forest Survey Research Note no. 1, 1942. 10 pp.; Photogrammetric Engineering v. 8, no. 2, p. 100-109, April-June 1942.

Shepherd, G. J. V. The interpretation of aerial photographs. Royal United Service Institution, Journal v. 70, p. 279-287, May 1925.

Shippee, Robert. The "Great Wall of Peru" and other aerial photographic studies by the Shippee-Johnson Peruvian Expedition. Geographical Review v. 22, no. 1, p. 1-29, Jan. 1932; Smithsonian Institution, Annual Report for 1932, p. 461-473, 1933.

Simons, A. L. Luchtopname en luchtverkenning (Ervaringen met deze methode op geolisch en ander gebied uit verschillende landen). De Ingenieur in Nederlandsch-Indië jg 7, no. 1, IV p. 1-22, Jan. 1940.

Smith, Derryfield N. Photo interpretation: Mata Hari with a glass eye. Photogrammetric Engineering v. 8, no. 1, p. 26-29, Jan.-Mar. 1942 .

Smith, H. I. Aerial photographic mosaic solves many problems in the Tri-State district. Engineering & Mining Journal v. 126, p. 706-708, Nov. 3, 1928.

***Smith, Harold T. U.** Aerial photographs in geomorphic studies. Journal of Geomorphology v. 4, no. 3, p. 171-205, Oct. 1941; Photogrammetric Engineering v. 8, no. 2, p. 129-155, April-June 1942.

*——. Aerial photographs and their applications. N. Y., Appleton-Century, 1943. 372 pp. $3.75.

Stamp, L. Dudley, comp. & ed. The aerial survey of the Irrawaddy Delta forests (Burma). Notes embracing the observations of Messrs. A. W. Moodie, C. R. Robbins and C. W. Scott. Journal of Ecology v. 13, no. 2, p. 262-276, Sept. 1925.

***Stokes, W. E. D., Jr.** Report of A.I.M.E. aviation committee for year 1936-1937. American Institute of Mining & Metallurgical Engineers, Transactions v. 126, p. 582-602, Discussion p. 603-606, 1937.

Talley, Benjamin B. Engineering applications of aerial and terrestrial photogrammetry. N. Y., Pitman, 1938. 612 pp. $10.

Taylor, Frank B. Recent advances add greatly to aerial photography value. Oil Weekly v. 93, p. 34-35, 38, 40, 42, Mar. 13, 1939.

Thomas, Hugh Hamshaw. Aircraft photography in the service of science. Nature v. 105, p. 457-459, June 10, 1920.

——. Aircraft photography in war and peace. Royal Society of Arts, London, Journal v. 68, no. 3543-3544, p. 763-766, Oct. 22, 1920, p. 777-781, Oct. 29, 1920.

——. Some features in the present position of aerial photographic survey. Royal Aeronautical Society, Journal v. 28, no. 163, p. 475-491, Discussion p. 491-500, July 1924; Flight v. 16, no. 9, p. 121-122, Feb. 28, 1924.

Tieje, Arthur J. The study of geology by aeroplane. Science n.s. v. 69, p. 301-302, Mar. 15, 1929; Engineering & Mining Journal v. 127, no. 19, p. 763, May 11, 1929.

Troll, Carl. Luftbildplan und ökologische Bodenforschung. Ihr zweckmässiger . . . Zeitschrift der Gesellschaft für Erdkunde zu Berlin Heft 7-8, pp. 241-298, Sept. 1939.

***Underhill, Harold.** Notes on reading air photos. Michigan Dept. of Conservation. Geological Survey Division, Lansing, [1935]. 6 pp.; Michigan Academy of Science, Arts & Letters, Papers v. 21, p. 285-291, 1935.

U. S. Cavalry School. Map and aerial photograph reading. rev. ed., Ft. Riley, Kansas, 1939. 244 pp.

U. S. Department of Agriculture. Flood Control Advisory Committee. Proceedings of seminar on aerial photography in flood control surveys, Dec. 6-8, 1939. 1940. 45 pp.; Appendix A. Preliminary draft. The use of aerial photographs and mosaics with particular reference to flood control surveys. 19 pp.; Appendix B, Wilson, R. C. Preliminary instructions for vegetation type map and cultivated land classification in California forest survey. 8 pp.

U. S. War Department. Topography and surveying. Map and aerial photograph reading. Training Manual TM 2180-5, prepared under direction of the Chief of Engineers, Sept. 28, 1938. 152 pp.

———. Topographic drafting. Technical Manual TM 5-230, 1940. 302 pp. $1.

———. Elementary map and aerial photograph reading. Basic Field Manual FM 21-25, prepared under direction of the Chief of Engineers, April 12, 1941. 100 pp. 30 cents.

———. Advanced map and aerial photograph reading. Basic Field Manual FM 21-26, prepared under direction of the Chief of Engineers, Sept. 17, 1941. 190 pp. 20 cents.

———. **Military Intelligence.** Role of aerial photography. Basic Field Manual FM 30-21, Nov. 1940. 89 pp. (Restricted.)

Vivian, C. H. Engineering from the sky. Compressed Air Magazine v. 39, no. 5, p. 4422-4427, May 1934.

Volla, Fernando & F. Porro. Fotografia aerea negli usi civili e militari; fotografare, interpretare, misurare la terra dall'aeroplano. Milano, U. Hoepli, 1932. 454 pp.

Volmat, J. La application de la photographie aérienne à l'hydrographie. Revue Maritime n.s. v. 1, no. 54, p. 725-752, Juin 1924.

Walker, George L. Prospecting for copper by airplanes. Engineering & Mining Journal v. 122, p. 576-578, Oct. 9, 1926.

———. Surveying from the air in central Africa. Engineering & Mining Journal v. 127, p. 49-52, Jan. 12, 1929.

———. Surveying the Witwatersrand from the air. Engineering & Mining Journal v. 135, no. 10, p. 456-457, Oct. 1934.

Washburn, Bradford. Morainic banding of Malaspina and other Alaska glaciers. Geological Society of America, Bulletin v. 46, no. 12, p. 1879-1890, Dec. 31, 1935.

White, Z. Waters. Aerial photography and its use in forest management. Master of Forestry Thesis, Yale School of Forestry, Feb. 1938. 51 pp. & 9 pp. bibliography.

Whitmore, George D. Elements of photogrammetry. Scranton, Pa., International Textbook Co., 1941. 136 pp. $1.85.

Wieslander, A. E. & R. C. Wilson. Classifying forest and other vegetation from air photographs. Photogrammetric Engineering v. 8, no. 3, p. 203-215, July-Sept. 1942.

Wilcox, Frank R. The use of aerial photogrammetry and aircraft in woods operations. Journal of Forestry v. 36, no. 10, p. 1038-1044, Oct. 1938.

* **Willett, R. W.** Air photography and geology. New Zealand Journal of Science & Technology, Sect. B, v. 22 (1B) p. 21-33, July 1940.

* **Williams, Neil.** Can aerial geology locate productive oil and gas areas? Oil & Gas Journal v. 30, no. 35, p. 11, 80, Jan. 14, 1932.

Willis, Bailey. Aerial observation of earthquake rifts. Seismological Society of America, Bulletin v. 11, no. 2, p. 136-139, June 1921; Science n.s. v. 54, p. 266-268, Sept. 23, 1921.

Winchester, Clarence A. C. & F. L. Wills. Aerial photography. A comprehensive survey of its practice and development. Boston, American Photographic Pub. Co., 1928. 251 pp. $10.

Woolnough, Walter G. Report on aerial survey operations in Australia during 1932. Canberra, Australia, L. F. Johnston, Commonwealth Govt. Printer, 1933. 83 pp.

*——. Notes on the technique of aerial photographic survey for geological purposes in Australia. 1st World Petroleum Congress 1933, Proceedings v. 1 Geological & Production Sections, p. 210-219, London, 1934.

——. Results of experimental aerial survey in Australia; with special reference to oil prospecting. 1st World Petroleum Congress 1933, Proceedings v. 1 Geological & Production Sections, p. 220-226, London, 1934.

——. The aeroplane in the service of geology. Royal Society of New South Wales, Journal & Proceedings v. 70, no. 1, p. 39-62, 1937.

Zuber, Stanislas. Méthodes d'application de l'avion et de la photographie aux recherches géologiques. International Congress of Mines, Metallurgy & Applied Geology, Liége, 1930. 6th Session, Sect. Geology, p. 425-430, 1931.

RECENT BIBLIOGRAPHIES ON AERIAL PHOTOGRAPHY AND RELATED SUBJECTS

American Society of Photogrammetry. Committee on Nomenclature. Definitions of terms used in photogrammetric surveying and mapping. Photogrammetric Engineering v. 8, no. 4, p. 247-283, Oct.-Dec. 1942.

American Society of Photogrammetry. Committee on Bibliography. Bibliography of photogrammetry and its applications up to 1936. Photogrammetric Engineering v. 2, no. 4, 117 pp., Oct.-Dec. 1936.

Bibliographie des publications photogrammétriques francaises parues depuis l'origine jusqu'a l'année 1937 incluse, présentée à la Commission 8 du Congrès International de Photogrammétrie, Rome 1938. Bulletin de Photogrammétrie 8 année, no. 2, p. 84-122, April-June 1938.

Deutsche Gesellschaft fur Photogrammetrie. Mehrsprachiges Wörterbuch für Photogrammetrie. (Multi-lingual dictionary for photogrammetry. German-English-French-Italian-Spanish) Berlin, 1934. 128 pp.

Dunbar, Clarence P. and L. M. Dunbar, comps. Aerial mapping, photography and surveying, prepared by the Technical Dept., Tulsa Public Library, Mar. 1937. 17 pp. (mimeo.) in: Supplement to a selected list of periodicals, serials, & books dealing with petroleum & allied subjects . . . La. Dept. of Conservation, New Orleans, June 1939.

Fersman, A. E., ed. Bibliography of air survey. Pt. 2. Research Institute of Geodesy & Cartography, Section of Aerial Photography, Transactions v. 6, Leningrad, 1931. 92 pp. (Pt. 1 issued as supplement to v. 1 of Transactions, 1930. 61 pp.)

Haferkorn, Henry E. Aerial photography. Bibliography of available material relating to the means, methods, experiments and results of aerial photography. Pt. 1. Photo-topography and kindred subjects; Pt. 2. Balloon photography, including kite—pigeon—rocket—cameras; Pt. 3. Aviation maps, including land marks, etc. Wash. Barracks, D. C., Press of the Engineer School, 1918.

Haquinius, Eric and E. A. Shuster, Jr., comps. Bibliography of photomapping and allied subjects. U. S. Geological Survey, Section of Photomapping, 1929. 84 pp. (mimeo.)

Lincoln, Francis C. The airplane in mining. The Black Hills Engineer v. 17, no. 2, p. 103-123, Mar. 1929. Bibliography p. 119-122.

Simons, A. L. Luchtopname en luchtverkenning, Ervaringen met deze methode op geologisch en ander gebied uit verschillende landen). De Ingenieur in Nederlandsch-Indië jg. 7, no. 1, IV, p. 13-22, Jan. 1940.

Steinmann, J. Vernon. Aerial photography. A book list. The Booklist v. 37, no. 18, p. 479-484, June 1941.

Troll, Carl. Luftbildplan und ökologische Dodenforschung. Ihr zweckmässiger . . . Zeitschrift der Gesellschaft für Erdkunde zu Berlin Heft 7-8, p. 241-298, Sept. 1939. (numerous bibliographic footnotes).

U. S. Works Progress Administration. Bibliography of aeronautics. Pt. 30—Aerial photography, compiled from the Index of Aeronautics of the Institute of the Aeronautical Sciences, 30 Rockefeller Plaza, New York City. Mar. 1939. 207 pp. (mimeo.)

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 54, PP. 1211-1226, 2 PLS., 1 FIG. AUGUST 1, 1943

METAMORPHISM OF EXTRUSIVES BY BASIC INTRUSIVES IN THE KEWEENAWAN OF MINNESOTA

BY GEORGE M. SCHWARTZ

CONTENTS

	Page
Abstract	1211
Introduction	1212
Acknowledgments	1212
Geologic relations	1213
Normal extrusives	1214
Contact metamorphic facies of the extrusives	1214
Textures	1214
Mineralogy of the basic facies	1215
General statement	1215
Feldspars	1216
Pyroxene	1217
Magnetite-ilmenite	1218
Olivine	1218
Hornblende	1218
Biotite	1218
Secondary minerals	1218
Minerals derived from amygdules	1219
Mineralogy of the acidic facies	1220
Chemical data	1221
References cited	1223

ILLUSTRATIONS

Figure	Page
1. Tabulation of important minerals of 64 hornfelses	1216

Plate	Facing page
1. Photomicrographs of basalt hornfelses	1224
2. Photomicrographs of basalt and rhyolite hornfelses	1225

ABSTRACT

The basalts and rhyolites of the Keweenawan of Minnesota have been invaded by the huge mass of the Duluth gabbro as well as by a great number of smaller sills, dikes, and irregular intrusives, mainly diabase. Close to the contact the flows are generally altered to fine granoblastic rocks which may not differ radically from the originals in mineral and chemical composition but are easily recognized by their texture. In the basalts the tendency is clearly to form a mineralogically simple rock consisting of plagioclase, pyroxene, and magnetite-ilmenite. The rhyolites tend to form a granular aggregate of acidic feldspar and quartz with minor amounts of other

minerals. Dehydration is the important chemical process in the development of the hornfels, but above the gabbro hydrothermal conditions at places may have prevented the formation of hornfels.

The characteristics of the metamorphism here described are peculiar to the effect of basic intrusives which in general form anhydrous minerals and a rock with granular texture with little sign of stress effects.

INTRODUCTION

The northeastern portion of Minnesota lying north of Lake Superior is an area of over 4000 square miles underlain almost entirely by Keweenawan extrusives and intrusives. There are probably 30,000 feet of extrusives of which 20,000 feet, lying between the basal Keweenawan sandstone near Duluth and the city of Two Harbors, has been carefully measured by Sandberg (1938). An additional 2500 feet was measured by Grogan (1940) between Two Harbors and the mouth of Split Rock River. Detailed work in progress shows that there is a considerable thickness of flows represented between Split Rock River and Two Islands in Cook County where the stratigraphically highest flow is exposed along the Minnesota coast. Intruding these flows, the Duluth gabbro, one of the large basic intrusions of the world, has a curving half-moon shape with an exposed length of over 160 miles and an estimated maximum thickness of possibly 50,000 feet (Grout, 1918). Above the gabbro and cutting the flows, often with great complexity, is a series of basic and lesser acidic intrusives. An unusual opportunity is thus afforded to study the contact metamorphic effect of basic intrusives on extrusives formed not long before. The writer became interested in the problem during field work for a thesis in 1922 (Schwartz, 1924) and has been afforded many opportunities to carry on additional investigations during field work for the Minnesota Geological Survey in the area at intervals since 1922. The paper on the Ely Greenstone (Schwartz, 1924) gives an extensive review of the literature, and references are accordingly reduced to a minimum in the present paper.

ACKNOWLEDGMENTS

The writer is deeply indebted to Professor Frank F. Grout at whose suggestion the original work on contact metamorphism was begun. His interest in the problem has been continuous, and he has contributed many specimens as well as ideas.

Several assistants have taken part in the field work. To the Minnesota Survey the writer is indebted for support of the field work and permission to publish the results. Assistance in the laboratory work was provided by the research funds of the Graduate School of the University of Minnesota.

GEOLOGIC RELATIONS

The formations directly involved in the present problem are all of Keweenawan age. The Duluth gabbro along its base cuts formations of the Keweenawan, Huronian, and Archean systems. The metamorphism of several of these formations has been previously described (Schwartz, 1924; Grout, 1933; Grout and Schwartz, 1933) and need not be reviewed here. At both ends of its exposures in Minnesota, the gabbro intrudes Keweenawan flows which are exposed both below and above the gabbro in and near Duluth and also about 140 miles to the northeast in Cook County. A contact metamorphic zone hundreds of feet in horizontal extent is normal, and where the gabbro is thick and lacking in an acidic facies at the top the contact effect seems particularly widespread. Perhaps the best place to observe this is in Duluth north of Skyline Boulevard and west of Kenwood Avenue where extensive exposures are visibly recrystallized over a distance of half a mile. Where the gabbro has the red rock segregate at the top, the contact effect seems slight, and hydrothermal effects are more conspicuous.

Above the gabbro practically the entire Minnesota coast of Lake Superior and inland to the top of the gabbro is a maze of diabase intrusives cutting Keweenawan basalts and rhyolites. Many intrusives have a general sill-like form, but large dikes are common, and all variations in form between the two are known. Only a portion of this complex has been mapped in detail, but Grout and Schwartz (1939, Pl. 6) give a fair idea of the complex. The largest sill along the coast of Lake Superior is the Beaver Bay diabase sill which is hundreds of feet thick and fully 7 miles long (Grout and Schwartz, 1939, p. 22-40). The intrusives consist of diabases which include facies grading from troctolite, through olivine gabbro to normal gabbro, and red granite, locally abundant, closely associated with the diabase. Intermediate rocks are conspicuously absent. At places the two rock types show a gradation by mixtures of diabase and red rock (Schwartz and Sandberg, 1940), but at other places they are evidently separate intrusions.

The amount of recrystallization of the intruded rocks is naturally related to the size of the intrusives, but there are some exceptions. Certain dikes have a much greater effect than sills of the same thickness, suggesting that the dikes were feeders, and the passage of large amounts of hot magma probably heated the wall rocks much more than would a more static cooling mass.

Papers by Grout (1918), Grout and Schwartz (1939), and Schwartz and Sandberg (1940) furnish a wealth of detail on the petrography and chemical composition of the gabbro and sills, and these details need

not be repeated. Earlier work by N. H. Winchell and his assistants is still a valuable source of information on the problem.

NORMAL EXTRUSIVES

The flows have been recently described by Sandberg (1938) for the area near Duluth, and by Grout and Schwartz (1939) for an area midway along the Minnesota coast of Lake Superior northeast of Duluth. It is necessary here only to note the varieties. The flows of the Minnesota Keweenawan are mainly of two widely separated types generally referred to as basalts and rhyolites. Intermediate and ultrabasic flows are practically absent. The basic flows are classified as ophite, porphyrite, and melaphyre. Most flows are highly amygdaloidal in the upper portion, and this results in considerable variety in the mineralogy of the hornfels.

The common primary minerals of the basalts are labradorite, augite, olivine, and magnetite-ilmenite. Alteration is common, especially of the ferromagnesian minerals to chlorite and serpentine. The amygdaloidal zones are commonly much altered, and zeolites, agates, epidote, chlorite, quartz, calcite, and iron oxides occur as fillings and as alteration products. Oxidation of the iron minerals to hematite often gives the amygdaloidal zones a reddish color.

The rhyolites vary from felsitic to porphyritic in texture but are rather uniform in composition, containing mainly quartz and dusty red feldspar, usually soda-orthoclase (Schwartz and Sandberg, 1940, Table 1). The primary hornblende, usually not abundant, is now an aggregate of alteration products.

CONTACT METAMORPHIC FACIES OF THE EXTRUSIVES

TEXTURES

The most consistent and extensive change in the metamorphosed basic extrusives is textural. This is true in hand specimen and naturally even more evident in thin section. There is rather conspicuous convergence to type as a result of extensive crystallization, so that regardless of original texture, size and shape of grains, the product has a hornfels texture with only moderate variation in grain size (Pl. 1). The recrystallization often results in a brownish granular rock not unlike brown sugar in appearance, for which N. H. Winchell used the term muscovadite (muscovadyte). In this country petrographers seem to favor the term hornfels for the texture or for the rock facies. The term hornfels does not imply hornlike appearance but rather finely granular or sugary. Granulitic is the term much used in Europe, but Becke introduced the term grano-

blastic which has also been widely used. Microscopically the rock has a characteristic texture which is a result of the tendency of the pyroxene, olivine, and to a lesser extent magnetite to assume a globular, essentially equidimensional form. The term granoblastic texture serves but still does not designate the globular form of some of the constituents or the size limits.

Uniformity of size of grain seems to characterize the hornfelses. Some of the original flows are porphyritic and have been called porphyrites in the Lake Superior area. These make up about 12 per cent of the flows in the Duluth area according to Sandberg's (1938) estimates. The phenocrysts of the porphyritic flows naturally resist recrystallization longer than the groundmass; consequently the original porphyritic texture is often recognizable in the hornfels. Diabasic (ophitic) texture is characteristic of a great many of the basic flows, and in these the lathlike form of the feldspars often persists somewhat in the hornfels, but the euhedral plagioclase crystals become scalloped as the groundmass recrystallizes. In some sections pyroxenes occur as globular inclusions in the feldspar phenocrysts. Possibly these simply project into the crystal from above or below the plane of the section.

The acidic extrusives, mainly rhyolite, when recrystallized also become hornfels. The minerals are nearly equigranular quartz, red feldspar, and magnetite with subordinate ferromagnesian constituents; there is little of the globular tendency in the grains of any of these minerals (Pl. 2, figs. 4, 5).

MINERALOGY OF THE BASIC FACIES

General statement.—A brief examination of thin sections of the contact-metamorphosed basalts suffices to show that a very few minerals characterize the most severely metamorphosed facies. Table 1 shows that four minerals are present in all specimens—plagioclase, pyroxene, magnetite, and ilmenite. Hornblende is present rather consistently, but it is known from observation of gradational contacts that hornblende is converted to pyroxene close to the contact. Other fairly common recrystallization products are olivine, biotite, quartz, orthoclase, and apatite. Secondary or hydrothermal minerals—chlorite, serpentine, and epidote—occur in some but not in the most intensely recrystallized rocks. A few sections show retrogressive alteration of ferromagnesian minerals to chlorite and uralite. The hydrous nature of those minerals suggests hydrothermal conditions. Of much lesser importance but observed in some specimens are: sphene, talc, hematite, kaolinite, zircon, hisingerite, and limonite. There appears to be a strong tendency toward a simple mineralogic type consisting of plagioclase, pyroxene, and magnetite-ilmenite.

Feldspars.—In the metamorphosed basic flows plagioclase is abundant, usually free from much alteration. Most grains are anhedral and clearly recrystallized because the feldspars of normal flows are much more dusty

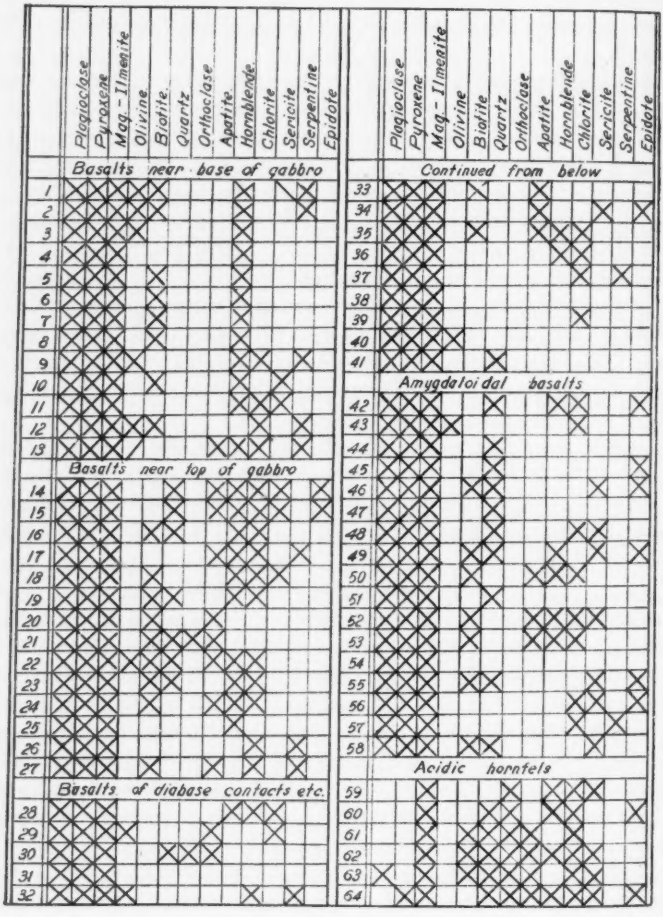


FIGURE 1.—*Tabulation of important numerals of 64 hornfelses*

with alteration products. In the incipient stages of the development of granoblastic texture, lath-shaped plagioclase crystals are scalloped. Feldspar phenocrysts are often cracked, and extinction is incomplete

particularly in exterior zones. Plagioclases range in composition, and it would be surprising if they did not, in view of the alteration to which the flows were subjected before contact metamorphism and also the contribution which amygdaloidal fillings have made to the composition of recrystallized amygdaloidal zones. About half the plagioclase tested is andesine, one-third labradorite, and the rest oligoclase-andesine, oligoclase, and andesine-labradorite. Orthoclase occurs in a few basic hornfelses derived from amygdaloidal zones.

Bytownite and anorthite were not discovered in any hornfels nor in the basalt flows away from contact zones. Bytownite does occur in the anorthosite found with diabases intrusive into the flows along the north shore of Lake Superior (Grout and Schwartz, 1939).

The most detailed modern work on the Keweenawan flows is that by Broderick (1935) on the flows of Keeweenaw Point. He found labradorite and andesine in the modes and the norms of these flows. Labradorite predominates, however, and is the average feldspar in the norms of both the thick flows studied in detail.

The evidence suggests that the plagioclase of the hornfels is slightly more sodic than that of the fresh flows.

Pyroxene.—The basic flows form hornfelses in which pyroxene is always abundant. Texturally, the pyroxenes play a most important role in the contact rocks as they tend to assume a globular form more than any other mineral, and the characteristic texture is thus closely related to the pyroxene content. The pyroxenes represent not only the recrystallization of pyroxene of the original rock but hornblende, chlorite, and possibly other minerals. Fine dustlike inclusions of magnetite are common in the pyroxenes of some specimens.

In the Keweenawan lava flows, augite is the common, though not exclusive, pyroxene. This was noted by Winchell (1900, p. 952) in his review of many years of work on the Keweenawan rocks of Minnesota. In the hornfelses derived from the Minnesota basic flows a variety of pyroxenes have developed. Augite is most common, but diopside and hypersthene also occur, and less commonly bronzite and enstatite. Two pyroxenes were found in several thin sections and are easily distinguished by variation in color, interference figure, and extinction angle. Diopside as colorless to slightly yellowish transparent grains was abundant in some recrystallized amygdules. It seems probable that augite is not as stable in the contact rocks as it is in the igneous rocks from which they were derived. This seems to agree with the generalized descriptions of pyroxenes in mineralogical texts.

Magnetite-ilmenite.—Magnetite and ilmenite are apparently more abundant in the basalt hornfels (Pls. 1, 2) than in the normal basalt flows of the Keweenawan. They occur as the usual octahedral intergrowths and as grains. In thin section it is not possible to distinguish between the two, and they are accordingly reported together. Selected specimens were polished, etched with boiling HCl, and studied microscopically. The relations observed were those commonly found in titaniferous magnetites and need not be described in detail.

The magnetite-ilmenite of the hornfels has evidently recrystallized to rather uniform size which is comparable to the size of the pyroxene grains (Pls. 1, 2).

The abundance of magnetite-ilmenite may be in part a result of contribution as noted below under chemical data, but probably a more important factor is the recrystallization of all or nearly all iron oxides of the original flows to magnetite.

Olivine.—Most hornfelses do not contain olivine, but in a few it is fairly abundant. Two factors seem important. The Minnesota basalts are mainly diabase in which olivine is not important. Secondly, olivine seems to form only very close to the contact where metamorphism is intense (Schwartz, 1924, p. 123). Olivine assumes the characteristic globular form, thus resembling pyroxene at least superficially.

Hornblende.—Many hornfelses, particularly those only moderately metamorphosed and several from near the top of the gabbro, contain hornblende in various amounts. Much of the hornblende is of the fibrous variety probably derived from augite. In some specimens, especially from above the gabbro, this is evidently hydrothermal in origin. Only rarely does it represent contact pyroxene that has retrogressed but as a rule it appears to be altered primary pyroxene or in some cases perhaps hornblende which developed during hydrothermal conditions.

Biotite.—Though not characteristic of the flow hornfels, biotite, at least in small amounts, occurs frequently. The most conspicuous occurrence is in a few contact rocks near or included in a diorite which occurs near or at the top of the gabbro in western Cook County. Here small biotite metacrysts with conspicuous poikilitic texture have developed (Pl. 2, fig. 1). In other localities the biotite occurs as scattered grains that have little effect on the general character of the rock.

Secondary minerals.—Chlorite, sericite, serpentine, epidote, and talc occur in some hornfelses. For the most part these seem to represent secondary, probably mainly hydrothermal, minerals which formed in the

basalts and have not been eliminated by recrystallization. They are, therefore, most abundant in the incipient and medium stages of the development of hornfels and are practically absent in the best hornfels. In some cases these hydrous and hydroxyl minerals may have developed in the contact rocks above the gabbro.

Minerals derived from amygdules.—Particular attention was paid both in the field and in the microscopic study to the amygdaloidal basalts which had been converted to hornfels. These rocks vary from dense, hard, fresh-looking, spotted rocks to those having a fine sugary texture. In hand specimen the original amygdaloidal character is usually evident because the amygdules are either light-colored or form small protuberances on the weathered surface. In thin section the original amygdule areas may be relatively inconspicuous if the metamorphism has reached an advanced stage.

The amygdules of the normal basalts of the north shore of Lake Superior are formed of the usual assemblages of zeolites, agate, various forms of quartz, calcite, epidote, chlorite, prehnite, iron oxides, apatite, and less commonly several other minerals. Of the zeolites, laumontite is most common.

On recrystallization during the formation of the hornfels the minerals of the normal amygdules disappear except quartz. Of the new minerals, feldspar is by far the most common. Some amygdules are converted mainly to feldspar; others, no doubt largely agate in original form, now occur as a mosaic of recrystallized quartz. In some rocks certain areas representing former amygdules are composed mainly of feldspar, whereas a near-by area is mainly of pyroxene. When feldspar is the sole or principal mineral of a recrystallized amygdule it has a fine mosaic texture which contrasts with the rounded grains of pyroxene which are abundant in some recrystallized amygdules. Magnetite is lacking or rare in most amygdule areas, but in a few it is abundant and may show a zonal arrangement (Pl. 2, fig. 2) resulting, no doubt, from a similar zoning of hematite or limonite in the amygdule.

Pyroxene in most recrystallized amygdules formed from chlorite or possibly from combinations of other minerals containing the necessary elements. In thin section some amygdules had a continuous narrow zone of pyroxene (augite) around the outside and an interior of granoblastic augite, quartz, and plagioclase. Coarse aggregates of pyroxene with a little feldspar compose some of the amygdule areas, with pyroxene notably coarser-grained than in the groundmass. Augite is common, but there is some orthorhombic pyroxene. Rarely a stringer of augite was observed; this probably represented an original chlorite veinlet. Biotite

was observed in several thin sections of amygdules; in some it occurs as small metacrysts and may have many inclusions similar to those in the biotite of nonamygdaloidal hornfels (Pl. 2, fig. 1).

Quartz normally forms a mosaic when it is the principal or sole mineral of a former amygdule. In the incipient stage of metamorphism quartz may have a fine cherty texture. Apparently very severe metamorphism of the rocks would be necessary to incorporate the quartz in the silicates of the basic rocks because many amygdaloidal hornfelses still contain abundant quartz.

One specimen contained a notable amount of apatite in recrystallized amygdules.

MINERALOGY OF THE ACIDIC FACIES

The acidic flows of the Minnesota Keweenawan are practically all rhyolites which consist mainly of pink feldspar and quartz. Feldspars are commonly euhedral and are almost invariably filled with earthy red hematite. Lesser minerals are augite, hornblende, magnetite-ilmenite, apatite, and secondary products, especially chlorite derived from the primary ferromagnesian minerals which are rarely fresh.

Good rhyolite hornfelses are not common for several possible reasons: (1) Rhyolite is much less abundant than basalt—Sandberg (1938, p. 827) estimates that in 20,000 feet of the Duluth flows one-eighth is rhyolite; (2) the known rhyolites are mainly above the Duluth gabbro where simple recrystallization is not as intensive as along the base of the gabbro; and (3) recrystallization in rhyolite may be slower than in basalt, perhaps because siliceous liquids are commonly viscous.

An excellent hornfels derived from rhyolite porphyry was observed near a granodiorite contact on the shore of Wine Lake in T. 63 N., R. 5 W. of western Cook County, Minnesota. The groundmass of the porphyry forms a fine-grained mosaic which includes primary phenocrysts dusty with alteration products; the edges are scalloped. The minerals are orthoclase, oligoclase, quartz, biotite, magnetite-ilmenite, apatite, zircon, chlorite, and sericite. Magnetite-ilmenite are more abundant than usual in an acidic rock; biotite is associated.

A recrystallized rhyolite at the contact of one of the sill-dike extensions of the gabbro in section 21, T. 63 N., R. 3 W., of Cook County is perhaps the most thoroughly recrystallized. The rock consists mainly of feldspar and quartz with a distinct sugary texture. Fibrous hornblende and magnetite-ilmenite with small amounts of sericite and chlorite are the lesser minerals.

A rhyolite porphyry very close to the upper gabbro contact was observed near 4th Avenue West between 5th and 6th Streets in Duluth.

The groundmass is recrystallized to a mosaic mainly of quartz and feldspar (Pl. 2, fig. 4) whereas the phenocrysts are cracked and healed with secondary feldspar and contain some epidote and calcite but evidently escaped recrystallization (Pl. 2, fig. 6).

Rhyolite within 50 feet horizontally from the upper contact of the gabbro was observed during the excavation of a sewer tunnel beneath First Street in Duluth. The rhyolite, like all the rocks observed in this tunnel, has been much altered by hydrothermal action rather than contact metamorphism. Post-gabbro faulting may have thrown these rocks into contact with the gabbro, otherwise it is difficult to explain the absence of contact metamorphism.

Ranta (1939) has described several examples of rhyolite inclusions in diabase and rhyolite in direct contact with gabbro. The writer has examined the thin sections of these examples. In the field stringers extend from rhyolite inclusions into the diabase leaving little doubt that some of the rhyolite actually melted. For the most part, however, the inclusion or zone along the contact recrystallized to a granoblastic texture which grades in a distance of a few feet at most to little-altered rhyolite porphyry. There is not much distinction between the stringers which were presumably molten and the portions which were merely recrystallized. Patterson (1942, p. 300) has recently described a somewhat similar example from Ireland where vein offshoots extend several yards out from xenoliths. Observation of these examples and examination of thin sections clearly show why confusion exists as to the exact process responsible for metamorphic changes near contacts. Under less clear conditions some geologists would no doubt refer the stringers to granitization.

CHEMICAL DATA

Glacial cover, confused relations, and the sill-like character of many of the intrusives make it only rarely possible to trace a specific contact rock very far. Thus good pairs of fresh and contact-metamorphosed specimens from the same flow were not usually obtainable. One occurrence of hornfels (Pl. 1, fig. 3), however, seemed so typical and well developed that it was selected for analysis as an example of the composition of the basic hornfels. The writer is indebted to A. E. Sandberg for calling his attention to this hornfels which occurs near the top of an exposure in a gabbro quarry near the 57th Avenue Station at Duluth.

Comparison of this analysis with Broderick's (1935) extensive analyses of Keweenawan basic flows shows that the silica in the hornfels is somewhat low. Alumina is lower than most, but two of Broderick's are still

lower, so the difference is not significant. Ferric iron is within the normal range, but ferrous iron is abnormally high. Magnesia, lime, soda, and potash are well within the normal range, but lime is somewhat above average. Low water content shows the essentially anhydrous nature of the minerals of the hornfels. Titanium oxide is more than

TABLE 1.—*Chemical analysis of hornfels inclusion in gabbro*

		Norm	
SiO_2	42.98		
Al_2O_3	13.09	Or	1.11
Fe_2O_3	3.16	Ab	18.34
FeO	13.38	An	25.30
MgO	6.44	Di	25.20
CaO	11.33	Hy	4.35
Na_2O	2.22	Ol	8.15
K_2O	.23	Mt	4.64
H_2O+	.51	Il	12.31
H_2O-	.04		99.40
TiO_2	6.52		
MnO	.21		
	100.11		

three times the average of the flows as given by Broderick. The diabase sills at Duluth (Schwartz and Sandberg, 1940) also have a much lower content of titanium than the hornfels. The high ferrous iron and titanium content combine to form ilmenite which makes up 12.31 per cent of the norm. Inasmuch as this is well above the ilmenite content of any of the Keweenawan basic flows analyzed, the conclusion seems justified that titanium and possibly ferrous iron have been contributed from the gabbro magma to the hornfels. In many thin sections of hornfelses the magnetite-ilmenite is notably abundant (Pl. 1). That the Duluth gabbro magma has contributed large amounts of titanium to inclusions of iron formation was shown by Broderick (1917, p. 670) in his work on the titaniferous magnetite deposits in Lake and Cook counties of Minnesota. In writing of inclusions of Gunflint iron formation in the gabbro, he says, "the contact effects of the gabbro upon inclusions were of the most profound nature, and the process of recrystallization was carried further than in rocks bordering the gabbro. There is evidence of the addition of titanium on a large scale to some of the inclusions."

The Gunflint formation away from the gabbro is practically nontitaniferous, but analyses tabulated by Broderick show that inclusions of banded Gunflint contain .30 to 10.61 per cent TiO_2.

It is apparent that the hornfelses form mainly by recrystallization of constituents present with the elimination of water. Close to the contact or in inclusions ferrous iron and titanium are added from the gabbro.

REFERENCES CITED

Broderick, T. M. (1917) *The relation of the titaniferous magnetites of northeastern Minnesota to the Duluth gabbro,* Econ. Geol., vol. 12, p. 663-696.

——(1935) *Differentiation of lavas in the Michigan Keweenawan,* Geol. Soc. Am., Bull., vol. 46, p. 503-558.

Grogan, R. M. (1940) *Geology of a part of the Minnesota shore of Lake Superior northeast of Two Harbors,* Ph. D. Thesis, Univ. of Minn.

Grout, F. F. (1918) *The lopolith an igneous form exemplified by the Duluth gabbro,* Am. Jour. Sci., 4th ser., vol. 46, p. 510-522.

——(1918) *A type of igneous differentiation,* Jour. Geol., vol. 26, p. 626-658.

——(1933) *Contact metamorphism of the slates of Minnesota by granite and gabbro magma,* Geol. Soc. Am., Bull., vol. 44, p. 989-1040.

——, and Schwartz, G. M. (1933) *The geology of the Rove formation and associated intrusives of northeastern Minnesota,* Minn. Geol. Survey, Bull. 24.

——————(1939) *The geology of the anorthosites of the Minnesota coast of Lake Superior,* Minn. Geol. Survey, Bull. 28.

Patterson, E. M. (1942) *A xenolithic minor intrusion at Slievengriddle, County Down,* Geol. Mag., vol. 79, p. 297-311.

Ranta, R. A. (1939) *Contact effects of basic magma on rhyolite,* M. A. Thesis, Univ. Minn.

Sandberg, A. E. (1938) *A section across Keweenawan lavas at Duluth, Minnesota,* Geol. Soc. Am., Bull., vol. 49, p. 795-830.

Schwartz, G. M. (1924) *The contrast in the effect of granite and gabbro on the Ely greenstone,* Jour. Geol., vol. 32, p. 89-138.

——, and Sandberg, A. E. (1940) *Rock series in diabase sills at Duluth, Minnesota,* Geol. Soc. Am., Bull., vol. 51, p. 1135-1179.

Winchell, N. H. (1900) *Geology of Minnesota,* Geol. Nat. Hist. Survey Minn., vol. 5.

University of Minnesota, Minneapolis, Minn.

Manuscript received by the Secretary of the Society, March 26, 1943.

PLATE 1.—PHOTOMICROGRAPHS OF BASALT HORNFELSES

Figure

1.—Fine-grained basalt hornfels. White is plagioclase, gray pyroxene and black magnetite-ilmenite. Collected near upper contact of the Duluth gabbro. St. Marie Street and Center Avenue, Duluth. × 21.

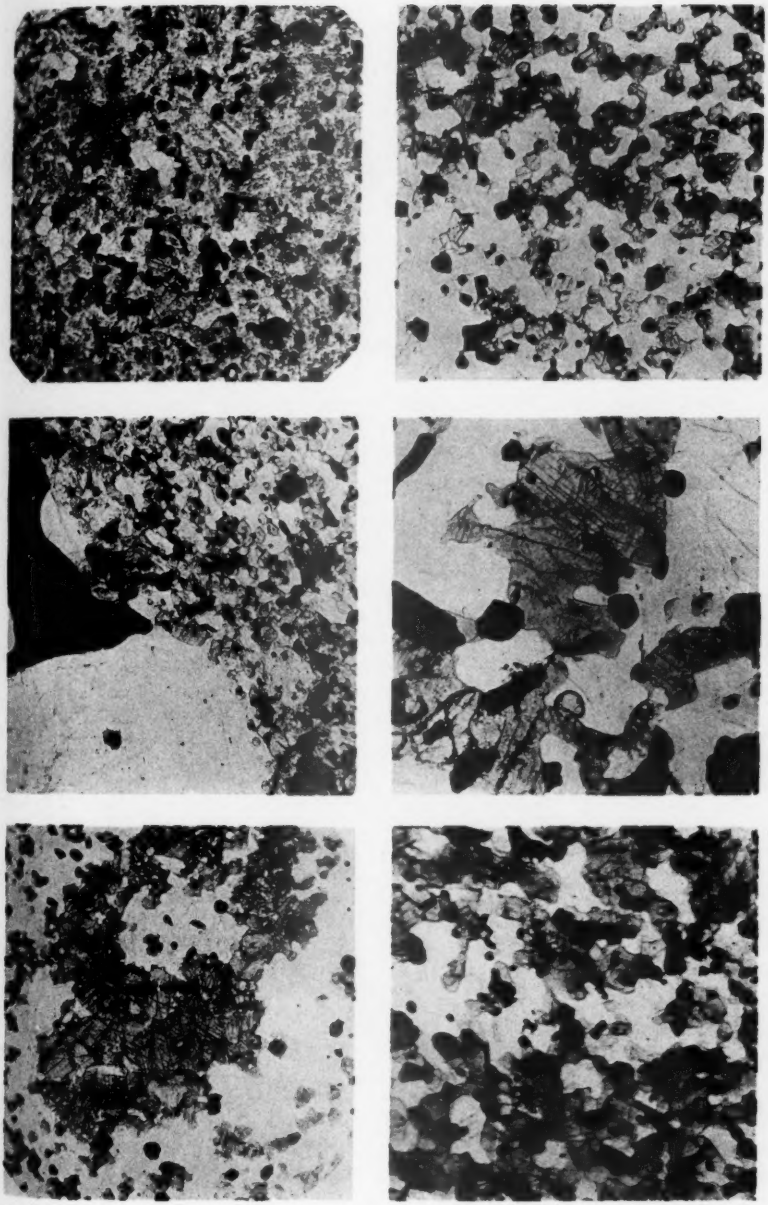
2.—Medium-grained basalt hornfels. Gabbro has soaked into this hornfels at the upper contact NW ¼, SE ¼, sec. 9, T. 50 N., R. 14 W. × 28.

3.—Contact of coarse gabbro and hornfels inclusion. Quarry at 59th Ave. W. and Columbia Ave., Duluth. × 25.

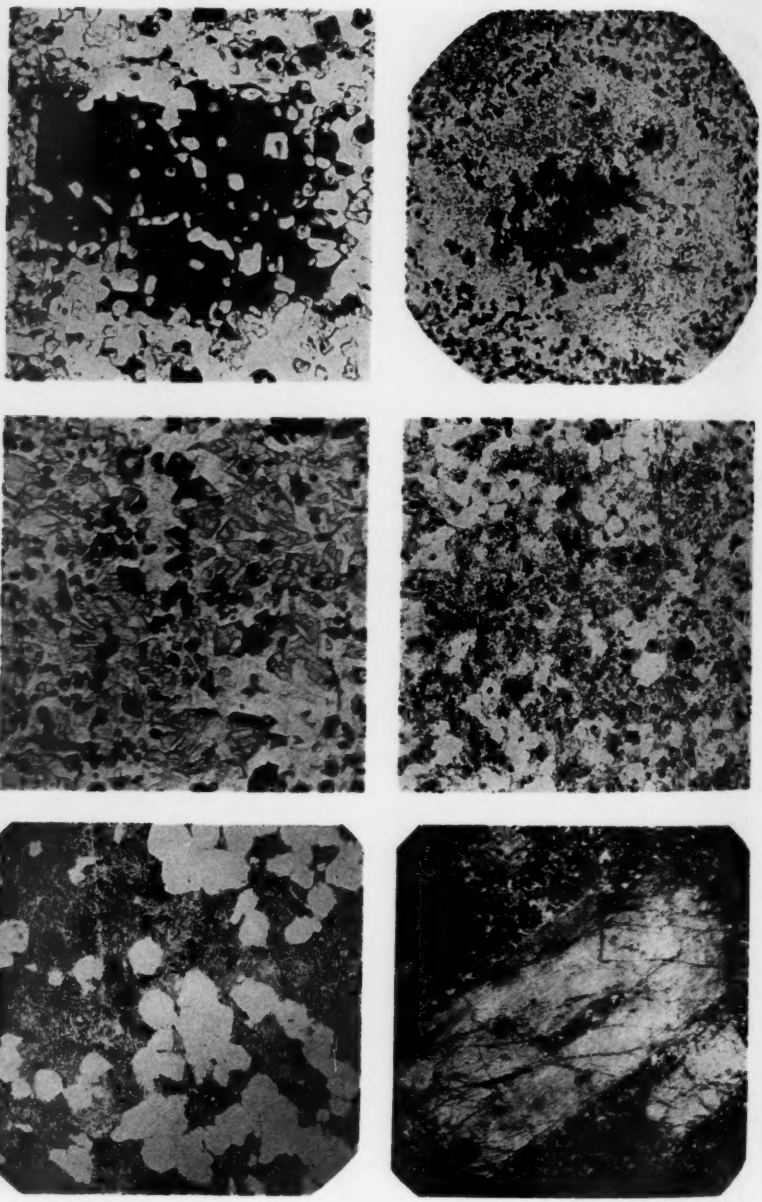
4.—Coarse basalt hornfels from an inclusion. Same location as Figure 3. × 28.

5.—Pyroxene aggregate in basalt hornfels. Remainder of slide plagioclase and pyroxene. Near upper contact of Duluth gabbro. 4th Ave. W. and 10th St., Duluth. × 21.

6.—Hornfels with high content of pyroxene and magnetite-ilmenite. White is plagioclase. 2nd Ave. W. and 2nd St., Duluth. × 28.



PHOTOMICROGRAPHS OF BASALT AND RHYOLITE HORNFELSES



PHOTOMICROGRAPHS OF BASALT HORNFELSES

PLATE 2.—PHOTOMICROGRAPHS OF BASALT AND RHYOLITE HORNFELSES

Figure

1.—Biotite metacryst in basalt hornfels. Island in Wine Lake. Cook County, Minnesota. × 35.

2.—Magnetite (black) zones in recrystallized amygdule. Basalt hornfels. Wine Lake area. × 30.

3.—High pyroxene (gray) area in basalt hornfels. Originally an ophitic patch. Southwest of mouth of Knife River, Lake Superior. × 40.

4.—Fine-grained rhyolite hornfels. Mainly quartz, feldspar (dusty gray), and magnetite. 4th Ave. W., between 5th and 6th Streets, Duluth. × 65.

5.—Rhyolite hornfels. Subhedral quartz grains with a red dusty feldspathic matrix. 2nd Ave. W., and 7th St., Duluth. × 21.

6.—Plagioclase phenocryst of a porphyrite (basalt) hornfels. The groundmass has a fine granoblastic texture. The phenocryst is fractured particularly at the ends. Quarry at Villa Scholastria, Duluth. × 21.